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Joint University Program for Air Transportation Research—1987

Proceedings of a conference held in
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January 14-15, 1988

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Joint University Program for Air Transportation Research—1987

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Proceedings of a conference sponsored by
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PREFACE

The Joint University Program (JUP) for Air Transportation Research is a coordinated set of three grants sponsored by NASA Langley Research Center and the Federal Aviation Administration (FAA), one each with the Massachusetts Institute of Technology (NGL-22-009-640), Ohio University (NGR-36-009-017), and Princeton University (NGL-31-001-252). These research grants, which were instituted in 1971, build on the strengths of each institution. The goals of this program are consistent with the aeronautical interests of both NASA and the FAA in furthering the safety and efficiency of the National Airspace System. The continued development of the National Airspace System, however, requires advanced technology from a variety of disciplines, especially in the areas of computer science, guidance and control theory and practice, aircraft performance, flight dynamics, and applied experimental psychology. The Joint University Program was created to provide new methods for interdisciplinary education to develop research workers to solve these large-scale problems. Each university, which submits a separate proposal yearly, is dealt with individually by NASA and the FAA. At the completion of each research task, a comprehensive and detailed report is issued for distribution to the program participants. Typically, this is a thesis that fulfills the requirements for an advanced degree or a report describing an undergraduate research project. Papers are also submitted to technical conferences and archival journals. These papers serve the JUP as visibility to national and international audiences.

An important feature of the program is the periodic review held at the schools and at a NASA or FAA facility. The 1987 review was held at the Federal Aviation Agency Technical Center, Atlantic City, New Jersey, January 14 to 15, 1988. At these reviews the program participants, both graduate and undergraduate, have an opportunity to present their research activities to their peers, to professors, and to invited guests from government and industry.

This conference publication represents the eighth in the series of yearly summaries of the program. (The 1986 summary appears in NASA CP-2502.) Most of the material is the effort of students supported by the research grants.

Four types of contributions are included in this publication: a summary of ongoing research relevant to the Joint University Program is presented by each principal investigator; completed works are represented by full technical papers; research previously in the open literature (e.g., theses or journal articles) is presented in an annotated bibliography; and status reports of ongoing research are represented by copies of presentations with accompanying text.

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Frederick R. Morrell
NASA Langley Research Center

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INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 1987

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SUMMARY OF RESEARCH

1. Introduction

There are three areas of research being pursued in 1987 under sponsorship of the FAA/NASA Joint University Research Program, and two other research projects were completed. The three active areas were:

- o Generation of Flexible Four-Dimensional Terminal Area Landing Paths

- o An Expert System for Runway Configuration Management

- o Modeling of Ice Accretion on Aircraft for Glaze Ice Conditions

The completed projects were: Automated speech recognition for air traffic control (ATC) (Reference 1), and automated scheduling of runway operations at major airports (Reference 2). Both of these areas are candidates for further research in future years.

2. Generation of Flexible, Four-Dimensional Terminal Area Landing Paths

If operations by aircraft landing and takeoff on multiple runways at a busy airport are scheduled to create an efficient sequence that maximizes capacity, then there remains a problem in determining a set of four-dimensional (4-D) paths for landing aircraft which is conflict-free and feasible within the performance and handling capabilities of each aircraft. These paths enter the terminal area at several entry fix points and may be initiated well beyond these entry points during busy periods. There may be several nominal paths (called Standard Terminal Arrival Paths (STARS)), from each entry point to each landing runway, which can be followed in the absence of other traffic. Around each nominal path, a pattern of paths can be constructed by introducing small variations in path parameters such as headings, speed reduction points, turn points, lateral spacings of downwind legs, and altitude reduction points. The research work reported by M. Sadoune as his S.M. thesis (Reference 3) addresses the problem of using an expert system approach to construct the set of paths within a pattern which, given an initial time and location, arrives at the landing runway at the same time. This work is continuing to introduce the problem of generating conflict-free paths and to study the transfer of the expert system code into a parallel processor environment. A set of annotated viewgraphs produced by M. Sadoune for his briefing at MIT in September 1987 is included in this report.

The Expert System approach is flexible and easy to maintain as ATC terminal area procedures change over time. This approach should provide a generic software that is easily transportable to many terminal areas where there will be a wide variety of constraints, geometries, and ATC procedures. The response time in generating terminal area flight paths must be small, since there will be unexpected operational deviations in the terminal area, such as landing aircraft missing their exit taxiway, missed approaches due to weather or traffic occupancy of the runway, change of runway direction, aborted takeoffs, blocked runways, and airborne emergencies. In these events, a sudden rescheduling of runway operations is necessary, and a quick redetermination of arrival paths for landing aircraft from their actual positions must be made. These problems (and others) are discussed in Reference 4.

3. An Expert System for Runway Configuration Planning

At major airports in the USA, there are perhaps 30 or more runway configurations for operating the airport when the assignment of takeoff and landing operations by class of aircraft to runway directions is considered, along with intersection takeoffs, "hold short" landings, and dry or wet surface conditions. There are numerous factors and constraints (operating rules, wind speed, direction, and visibility, noise policies, snow removal, status of approach facilities, and runway maintenance needs) which affect runway availability at various points in time. It is a difficult task to know which configurations are available at any time, and an even more difficult task to plan a schedule of operating configurations for the airport over the next several hours based on forecast availabilities. There may be a limited number of transitions between pairs of runway configurations and a loss of capacity during certain transitions. During low traffic periods, it is desirable to give local communities under the approach and departure flight paths some relief from aircraft noise. It is not desirable to have configuration changes too rapidly or to have them occur as ATC controllers are changing shifts. If it is snowing, the type and rate of snowfall and the ability to clear out-of-use portions of runways and taxiways with plows, chemical, and brush equipment for quick transition to operating status are factors in planning changes in runway configurations. If it begins to rain, the condition of grooved runway surfaces determines the feasibility of continuing hold-short landing operations that allow independent landing approach spacing, and therefore affects airport capacity. This ongoing research project is investigating the application of expert systems technology to the runway configuration planning problem.

Every airport will have a different problem, although there is some degree of commonality. If conventional computer programming techniques are used, it is difficult for programmers to support the constantly changing set of operating procedures at any major airport, since computer codes would have to be customized to each airport. The expert system approach theoretically overcomes these difficulties by allowing a generalized set of operating rules and procedures to be maintained by ATC supervisory personnel to meet their changing needs. This expert system must operate in real time, as a "truth maintenance" system keeping track of current weather and traffic forecasts and equipment status, and modifying a planned set of times for changing runway configurations. This schedule information can be disseminated to various area supervisors in local ATC facilities and local and national flow control managers who are interested in future airport capacity and its changes, both up and down, as runway configurations are changed.

At present, an expert system "core," called "Tower Chief," is being created to see if a useful Runway Configuration Planning System (RCPS) can be built. A paper presented by Lyman R. Hazelton, Jr. at the Princeton Research Progress Review Meeting in April 1988 is included in this report.

4. Modeling for Ice Accretion on Aircraft in Glaze Icing Conditions

The work in aircraft icing over the past year has focused on the fundamental aspects of glaze ice accretion, with the goal of improving analytical ice accretion models. Current ice accretion models do not perform well within the glaze ice regime. Glaze icing is characterized by rough and irregular ice accretions and occurs at relatively warm temperatures, i.e., a few degrees below freezing. In this regime the ice accretion is controlled by the removal of latent heat by convective heat transfer. This heat transfer is strongly dependent on the roughness of the ice surface. Current ice accretion models assume a uniform ice surface roughness that is an input parameter in the models. Over the past year, studies have been conducted on the generation of surface roughness on accreting ice surfaces with the goal of providing a deterministic surface roughness in the ice accretion models.

A series of icing wind tunnel tests were conducted on simple circular cylinders at an icing test facility, courtesy of Data Products of New England. The evolution of ice surface roughness was carefully monitored during these tests. Several distinct zones of surface roughness were observed. These include a smooth zone in the stagnation region, a rough zone somewhat downstream, and a runback zone farther aft on the cylinder. Each zone exhibited distinct water runback and surface roughness characteristics. The location of transition between the smooth and rough zones was observed to propagate toward the stagnation region during the icing encounter. Based on these preliminary experiments, a relatively simple modification to the existing ice accretion models has been proposed. Instead of a single uniform roughness, several zones of surface roughness are considered. Preliminary analysis of this Multi-Zone Roughness model has indicated the potential for significant improvements in the performance of analytical models in the glaze ice regime. Further tests of the Multi-Zone model are scheduled in the Icing Research Tunnel at NASA Lewis Research Center for the next year. The details of the initial wind tunnel experiments and the model are presented in an AIAA paper presented at the 1988 Aerospace Sciences Meeting (AIAA-88-0015).

ANNOTATED REFERENCES OF 1987 PUBLICATIONS

1. Trikas, T.: Automated Speech Recognition in Air Traffic Control, FTL Report 87-2, January 1987, Flight Transportation Laboratory, MIT, Cambridge, Ma 02139.

   Over the past few years, the technology and performance of Automated Speech Recognition (ASR) systems have been improving steadily. This has resulted in their successful use in a number of industrial applications. Motivated by this success, a look was taken at the application of ASR to Air Traffic Control, a task whose primary means of communications is verbal.

   In particular, ASR and audio playback were incorporated into an Air Traffic Control Simulation task in order to replace "blip-drivers," people responsible for manually keying in verbal commands and simulating pilot responses. This was done through the use of a VOTAN VPC2000 ASR continuous speech recognition system that also possessed a digital recording capability.

Parsing systems were designed that utilized the syntax of ATC commands, as defined in the Air Traffic Controller's Handbook, in order to detect and correct recognition errors. As well, techniques whereby the user could correct any recognition errors himself were included.

Finally, some desirable features of ASR systems to be used in this environment were formulated based on the experience gained in the ATC simulation task and parser design. These predominantly include continuous speech recognition, a simple training procedure, and an open architecture to allow for the customization of the speech recognition to the particular task at hand required by the parser.

2. Trivizas, D. A.: Parallel Combinatorial Search - Its Application to Runway Scheduling, FTL Report 87-4, February 1987, Flight Transportation Laboratory, MIT, Cambridge, Ma 02139.

The Runway Scheduling Problem (RSP) addresses the fundamental issues of airport congestion and energy conservation. It is a variation of the Traveling Salesman Problem (TSP) from which it differs in three basic points: the maximum position shift (MPS) constraints, the requirement to enforce the triangular in its cost structure, and the multiplicity of runways (corresponding to multiple salesman in TSP).

The RSP is dynamic, requiring fast and frequent schedule updates. The MPS constraints, designed to prevent inequitable treatment of aircraft, define a combinatorial neighborhood of tours around a base tour, determined by the arrival sequence of aircraft in RSP. The neighborhood contains all tours in which the position of an object (aircraft, city, etc.) in the new tour is within MPS positions of its position in the base tour. The parameter MPS controls the radius of the neighborhood, which covers the full solution space when MPS equals half the number of aircraft.

We first describe the RSP and then develop a parallel processor (ppMPS) that finds the optimal solution in the MPS-neighborhood in time linear to the number of objects, using up to 4 MPS processors in parallel. Subsequently, ppMPS is applied to the general RSP, and a case study is presented to justify simplifying assumptions in the scheduling of mixed traffic on multiple runways. The case study shows substantial improvements in the capacity of a system of three runways.

Suggestions are made on how to use the ppMPS to create fast heuristic procedures for the TSP, based on divide and conquer and node insertion strategies.

3. Sadoune, M.: An Expert System for Generating Terminal Area Flight Paths for Arriving Aircraft, FTL Report 87-10, July 1987, Flight Transportation Laboratory, MIT, Cambridge, Ma 02139.

Air-traffic congestion and frequent saturation of major airports require improved Air Traffic Control procedures to make the flow of traffic more uniform and to increase system capacity. Advanced technologies allow an increased aircraft controllability that makes trajectory planning feasible.

A computerized Flight Path Generator for Air Traffic Control has been designed and is described herein. This tool is intended to aid controllers in their decision-making process for guiding aircraft to the runway before landing. The flight path generation program has been developed in the form of an Expert System in a Prolog and Lisp environment.

A computationally tractable symbolic representation framework for aircraft motion in space is introduced. Several Artificial Intelligence techniques are combined to design a planner, based on partially predefined sequences of actions involving mathematical descriptions, such as movement in space with a time requirement.

The adequacy of an Expert System to develop new flight approach procedures and adaptive separation criteria is highlighted. Symbolic conflict detection and resolution are presented as an extension to the Flight Path Generator in an Expert System environment.

4. Simpson, Robert W.: Expert Systems for the Generation of Terminal Area Arrival Paths for Civil Transport (1989 AGARDO graph GCP/AG 301, Computation, Prediction, and Control of Aircraft Trajectories, A. Benoit (editor)).

Efficiencies can be gained from dynamic scheduling of the takeoff and landing operations for the system of runways at a major civil airport. It is then necessary to be able to generate a conflict-free set of flight paths which implements this schedule and which can be easily changed. For landing arrival aircraft, these flight paths start at a known time, point and speed in the descent toward the airport, and end at a reduced speed and time at the outer marker of the final approach to the assigned runway where desired in-trail separations must be achieved.

To generate sets of conflict-free arrival paths, an "Expert Systems" computer program finds and selects a path feasible within the performance limits of each aircraft from a set of "patterns" which is easily understandable by the human controller. This technique is easily adaptable to the geometric characteristics of different terminal areas and runway configurations and accepts rules and procedural limitations that can be specified and implemented by ATC controllers themselves, as desired.

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Tower Chief — An Expert System for Runway Configuration Planning

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1 INTRODUCTION

The FAA *National Airspace System Plan*[1] forecasts that the demand for aviation services will double within the next fifteen years. This demand for air transportation in the United States over the next decade has brought with it a requirement for a better organized and more efficient control system. The increasing number of aircraft which are active within the system at any time presents some novel problems with which the current control system appears to be unable to cope.

In particular, the present FAA/NAS (National Airspace System) is occasionally operating near the limits of its capacity in the near airport regions of some of the nation's larger airports. This capacity isn't always the same as the theoretical maximum capacity of the runway system since the system may be limited by the airspace around the airport as well. If aircraft arrive stochastically at the average rate which would saturate the runway system, queues will form requiring aircraft to be stacked in "holding patterns". During VMC[2], most airports even today have a higher capacity than the demand made upon them, so little queuing occurs. However, when the weather deteriorates to IMC[3], the capacity of the the airport generally decreases below that necessary to handle all of the incoming aircraft. If the demand is allowed to stay at the VMC level, stacking will be required. Before the air traffic controllers' strike in 1981, the system was actually operated in this manner.

During the 1981 strike, in order to allow the system to continue to operate with a drastically reduced controller force, constraints were placed on the demand to seriously limit or avoid the formation of stacks. These constraints took the form of "gate holds". In essence, the aircraft are queued on the ground instead of in the air. To manage this task, a new controlling body was formed, called the *National Flow Control System.* In the name of safety and fuel conservation, this system is still in use today, and the gate hold has become infuriatingly familiar to many airline passengers.

Essentially, the flow control system is supposed to operate in the following manner:

---

[1] See reference [1], page II-1 and following.

[2] Visual Meteorological Conditions, see FARS, reference [2].

[3] Instrument Meteorological Conditions, see FARS, reference [2].

The landing demand[4] at any major airport is a fairly well known figure. Long term estimates can be produced from the *Official Airline Guide*, while shorter term forecasts can be calculated using filed flight plans and position reports of enroute aircraft. Airport capacity[5] is predictable as well, although it is a much more elusive quantity. Capacity is most strongly affected by the *airport configuration*, i.e. the runways in use and the associated approach and departure procedures.

Given the expected capacity and demand of the destination airport, flow control is designed to guarantee that the demand never exceeds the capacity and the traffic arrives in a homogeneous stream. Each hour, a limited number of landing time slots are available. To control the flow of aircraft into the destination airport, these slots are assigned to each inbound aircraft *before it takes off from its origin airport.* Since the number of slots is relatively small, there are occasions when all the slots for a given hour are filled. All other flights to the destination airport having an estimated time of arrival during this hour must be detained on the ground. Gate delays are assigned to these aircraft. The delayed flights are given landing slots in a future time period. Priority is based on the length of the gate hold. This process continues until all aircraft have been assigned slots.

Since information on predicted demand and capacity becomes less and less reliable in the future, there is an event horizon beyond which it is unrealistic to use the system. Given the average speed of a commercial air transport, this translates into a distance horizon. Thus, flights to a given airport that originate farther than the distance horizon must be exempt from the flow control process. Once enroute, a flight has priority to receive a landing slot. It is only considered for delay under extenuating circumstances, such as an emergency at the destination or on another flight, or if the capacity prediction was too high in the first place and the aircraft finds a congested airport on arrival.

On a fine, sunny day, when the parameters are changing slowly, prediction of demand and capacity can be made with considerable certainty, and the system works admirably. Most large airports under VFR[6] have capacity exceeding the current demand, and use of the flow control system is unnecessary. As the weather gets worse, or changes rapidly, the certainty of the predictions degrades and the planning horizon should shrink. However, allowing the planning horizon to contract beyond a certain limit would defeat the purpose of the flow control system. Instead, the horizon is held constant.

The flow control system attempts to juggle capacity and demand. On the one hand, if the actual capacity turns out to be greater than the demand, then there are unused slots and the airport is not being used to its fullest. On the other hand, if the demand allowed by the system exceeds the capacity, enroute and terminal area delays (*in flight*) will ensue, with their associated increased controller work load. The first condition is unfortunate and expensive in terms of lost capacity. The second scenario is more expensive in terms of wasted fuel, and may even be dangerous.

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[4] Number of aircraft per hour requesting to land.

[5] The number of operations (landings and takeoffs) per hour the airport can accommodate.

[6] Visual Flight Rules, see reference [2].

Clearly, one of the key factors to the success of the flow control system is the accuracy of the capacity and demand predictions. The availability of OAG[3], flight plan, and radar position data makes prediction of demand relatively easy. Capacity prediction, which depends on factors which are more difficult to measure or quantify, is harder. Since operating a jet transport is costly, and the number of flights involved is large, the return on even a slight increase of the throughput of the system is enormous. Thus, the interest in improving airport capacity prediction is high.

Because capacity depends to a great extent on the configuration, we must begin by looking at the factors which influence the configuration.

- Runway conditions.
- Wind velocity and direction.
- Ceiling and visibility.
- Time of day and season.
- Noise abatement procedures.
- Ratio of takeoffs to landings.
- Types of aircraft involved and the number of each type.
- Configurations in use at surrounding airports.
- Maintenance of runways and taxiways.
- Snow removal.

Commonly there are thirty to seventy configurations that can be used at major airports under different conditions. There can be well over a hundred at a very large installation such as O'Hare or Kennedy International. In addition, transitions between some configurations and others are very expensive[7]. The large number of choices of possible configurations, together with the complexity of the interactions between the factors just outlined, make the construction of a configuration plan over a several hour period a very difficult task. This, in turn, makes the prediction of airport capacity over such a period a process prone to much error and frustration.

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[7] Entry into the approach area may have to be suspended during the reconfiguration period.

Talks with *FAA* area supervisors at two airports (Boston Logan International and Miami International) indicate that configuration planning is *not* currently employed. Instead, a short term, tactical methodology is used. The area supervisor, acting on whatever information is available, decides what configuration is to be used at the *current time*. **There is no long term plan.** The numbers used for expected capacity in the flow control metering process are telephoned into Washington about every hour. How closely these estimates are to reality is a matter for conjecture.

The *FAA* has shown interest in computerizing configuration management for some time. Work on the O'Hare Runway Configuration Management System, an ongoing project of the Mitre Corporation[8], has been under way for over ten years. This system is a first generation expert advisor which can be used for analysis of a single configuration *transition*. The approach is to quantify all the data and use a linear programming optimization scheme to arrive at a ranking of a number of different configurations that might be employed instead of the one currently in use. It does no planning, and furthermore, the rules used by the system are hard coded into the FORTRAN program, making changes in the rules and installation at other airports excessively expensive.

It should be noted that some of the items in the aforementioned list, such as runway conditions and configurations at nearby airports, are very difficult to quantify. This fact makes the application of linear programming techniques cumbersome and artificial. Use of linear programming requires an objective function which is "optimizable" in some sense. The solution generated by the LP results in an *optimum*. However, the inclusion of arbitrarily quantified terms in the objective function leads to an artificial solution which has little basis in reality.

A configuration plan is a *pattern* of events which takes place over a period of time. It is a type of *strategic plan*, such as moves in a chess game. The configuration plan is altered based on forecast of future conditions. This is similar to the way a chess player plans a sequence of moves based on his prediction of the pattern of the pieces on the board later in the game. It has been shown that expert strategic planners, such as chess masters, do *not* attempt to compute their plan of attack. Instead, they recognize the pattern of the pieces on the board and are led by that pattern, and the changes within it as the game proceeds, to an overall game plan [9]. *Artificial intelligence* can be used to emulate this kind of pattern driven process.

The problem of constructing an airport configuration plan is a good candidate for an artificial intelligence solution. I propose to build an advisory airport configuration planner called *Tower Chief*.

---

[8] See reference [4].

[9] See reference [5].

2 System Description

There are four major goals of the *Tower Chief* system:

- keep the airport operating at **high efficiency**,
- provide the operator with a **configuration plan**,
- provide the operator with the **expected capacity** of the airport over the period of application of the plan,
- provide a **forecast of delays** given the volume of demand.

An airport can be considered as a set of runways. Each runway has an associated set of approaches for landings and may be used for arrivals, departures, or both. An *airport configuration* is the specification of some subset of the runways together with their use (arriving, departing, or both), and the approaches that are in use to the landing runways. It is possible that departure routes might be included as well.

Although it might be possible to create a system which would be capable of having as input all of the runway data and other information necessary to *enumerate* the list of all valid configurations for an airport, that is a separate issue. For the present research, I will assume the existence of some finite number of predetermined configurations for each airport.

The *capacity* of each configuration is a function which depends upon the weather, the ratio of departures to arrivals, the diversity of different sizes of aircraft that will be using the airport, and the particular tower team on duty. Analytical and simulation techniques[10] have been employed to estimate maximum capacities of configurations under differing weather conditions at some airports. The present research effort will focus on the configuration *planning process*. Capacities under differing conditions will be part of the input data describing each configuration.

A *configuration plan* is a sequence of configurations and the times at which transition from one configuration to the next in the sequence should take place. Although transitions from one configuration to another takes some time, I will assume (at least to begin with) that these intervals are included in the duration of each configuration segment. It is also true that making a transition has a cost, in terms of lost capacity. This cost depends on the initial and final configuration and the conditions under which the transition occurs. I will assume that this lost capacity is negligible. I know this is not true, as it takes up to ten to fifteen minutes for a change; perhaps an adjustment can be included after the primary planning process has been accomplished.

---

[10] Reference [6] contains an excellent bibliography of this work.

Traditionally, high capacity has been the objective of choosing a configuration. In some cases minimizing noise impact has been utilized instead. However, no one objective should be employed in all situations. Different measures must be applied to the performance of the planning system depending on conditions. For example, the overall capacity of the system might be maximized under conditions when the demand exceeds capacity. However, a lower capacity may be tolerated in exchange for:

- lower noise exposure to the surrounding population,
- making one or more runways available for other uses, such as snow removal or repairs,
- safety and pilot desirability (crosswinds, sun angle, over water, etc.),
- lower total number and complexity of transitions occurring over the duration of the plan (*i.e.* lower tower work load).

Plans created by the system should be judged by the same criteria that would apply in judging plans made by people, namely, "Can we do better?"

It cannot be stressed strongly enough that the *Tower Chief* system must operate in a highly dynamic environment. Only the geometric layout of the runway and approach systems are not subject to change. Other inputs to the system may be changed at any time. These changing inputs include:

- Weather (Wind, Ceiling, Precipitation, Visibility, etc.),
- Runway surface conditions,
- Noise abatement procedures, which change from day to night,
- Wake vortex avoidance (only under certain weather conditions),
- Requirements for snow removal and runway maintenance,
- ATC shift changes,
- Daily demand variation,
- Changing operator constraints, such as the number of controllers actually on duty.

In addition to the dynamic nature of the system, quite often the input data may be incomplete and/or self conflicting. In particular the system must contend with predicted data, possibly from more than one source, for weather and traffic flow rates.

A system using either Baysian or Demster-Schaffer "statistics" will have to be employed as a central part of the planner.

Tower Chief must be aware of the passage of time. As time passes, information about what is happening to the weather, traffic demand, and the actual configuration in use must be updated. Whenever new data become available, *Tower Chief* must re-evaluate the current plan. In this regard, it would be interesting to have the system connected to the National Weather Service and to the Flight Plan computer system so that this updating process would be automatic.

3 Assumed Usage Mode

Tower Chief is intended to be an **advisory** system. It is meant to be a tool for the use of tower or area supervisors to help organize and formalize airport operation. As any tool, its usefulness will be determined by its accuracy, its ease of use, and its breadth of applicability.

The proposed system would consist of three major parts. Geometric and state information should be contained in a "*model*" of the airport and its surrounding area. Strategies and rules of operation should be in a "*rule system*" which must communicate with the model. Like many "expert systems", *Tower Chief* will require a great deal of information for proper operation, so a good *user interface* will be necessary.

The model is initialized by loading it with the site specific geometry, current configuration, scheduled traffic, and current and expected weather for the next six to eight hours. Given this information, the rule system will generate a "best" plan for the period for which it has enough data, and will display the configuration plan. The user may then request an analysis and display of the performance measures (i.e. the expected capacity and average delays) of this machine-generated plan.

Non-destructive speculation about what effect changing data *or rules* might have on the nature of the final plan is an important capability. The user should be able to create a speculative set of weather data, assumed traffic, and perhaps rules, and then request that a plan be generated on the basis of these assumptions, and similarly analyzed. Should the user feel that the speculative plan is a better one than that created by the system using the original assumptions, that plan could be made the "current plan".

The system should be able to assist its operator in analysis of the plan generation process by providing explanation of any part of the process on demand. *Tower Chief* will be able to display the "reasoning" which lead to a given plan or any of its elements. This feature could be used for debugging the rule system as well as the training of personnel.

The symbolic representation of the rules will be as simple and meaningful as possible. English language translation of the rules will be available to help "debug" the rule system as well as give its users a better understanding of its structure.

4 Implementation

As described in the introduction, systems employing Artificial Intelligence have a basis in pattern recognition. In the case of expert systems, this pattern recognition is formulated by *rules*. In the general paradigm outlined above, the deductive process might be diagramed as

$$\textbf{if} < \text{pattern1} > \Rightarrow < \text{pattern2} >$$

meaning, "If the input data matches <pattern1>, then assert <pattern2>." In a rule based system, the antecedent of some rule constitutes the pattern to match, while the consequent of the rule becomes the pattern to assert if the match is successful. For example:

```
if traffic-mix is 20%-heavies
   and gusting is nil
   and cross-wind-component less-than 4kt
   and surface is foggy
then capacity is reduced-20%        ; cause is wake-vortex
```

Systems using only rule based inference have been studied for some time, and are not capable of maintaining their knowledge-bases when relationships change for some reason. This is because these systems lack any information to causally link different assertions. A subsystem which maintains the causal or evidentiary links between facts in the knowledge-base is called a *Truth Maintenance System* (See [7] or [8]).

Tower Chief will be implemented as a rule based inference system with an underlying truth maintenance system.

4.1 Software

A few development systems (ART [11] and KEE [12], for example) exist which seem to have the necessary qualifications for use as a core for *Tower Chief*. However, they are *very* expensive at the present time. As of this writing, none of them is available for use in the Flight Transportation Laboratory. Unless one of these systems can be obtained, it is suggested that the necessary programs be developed in house.

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[11] ART is a trademark of Inference Corporation.

[12] KEE is a trademark of IntelliCorp.

It is well established that the language of choice for development of expert systems is LISP. Common LISP programs are also easily portable to a wide variety of hardware and operating systems.

4.2 Hardware

The computer systems available for this work include a DEC/VAX 750, a Texas Instruments Explorer, an IBM-PC/AT, an Apple Macintosh, and an Apollo DN-3000. FTL's VAX is currently running NIL, but that implementation of LISP is no longer supported and may safely be considered dead. The TI Explorer running Common Lisp is a good candidate, as is the PC/AT running compiled Golden Common Lisp, or Lucid Common Lisp on an Apollo. Writing most of the code in Common Lisp[13] will give the broadest portability while retaining the strong symbol manipulation capability necessary for the project. Though this thesis is meant only to demonstrate the feasibility of using such a system as *Tower Chief*, it would be interesting to target the system on a machine that might be actually used in the field.

5 Knowledge Engineering and Test

There are several different sources for the knowledge necessary to create the knowledge base and rule base for *Tower Chief*. The Federal Aviation Rules [2] is a good start. For capacity data, the FTA study of Logan [10] is a great source. Many of the people in the Aero/Astro Department are pilots, including the author, and have direct experience with the subject from a pilot's viewpoint. The area supervisor at Logan International Airport has very kindly volunteered to be of assistance.

The system can be tested and exercised with real data from Logan while still at M.I.T. by monitoring of the ATIS[14] and using information taken from the OAG. Once this preliminary testing is completed satisfactorily, then a more realistic test might be attempted at the Logan tower.

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AN EXPERT SYSTEM FOR GENERATING TERMINAL AREA FLIGHT PATHS FOR ARRIVING AIRCRAFT

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Plan

Context

- Air-traffic congestion and frequent saturation of major airports require improved Air Traffic Control procedures to make the flow of traffic more uniform and increase system capacity.
- Advanced technologies allow an increased aircraft controllability that makes trajectory planning feasible.

Achievement

- A computerized Flight Path Generator for Air Traffic Control has been designed.
- This tool is intended to aid controllers in their decision-making process for guiding aircraft to the runway before landing.
- The flight path generation program has been developed in the form of an Expert System in a Prolog and Lisp environment.

Method

- A computationally tractable symbolic representation framework for aircraft motion in space is introduced.
- Several Artificial Intelligence techniques are combined to design a planner, based on partially predefined sequences of actions involving mathematical descriptions, such as movement in space with a time requirement.

Extensions

- The adequacy of an Expert System to develop new flight approach procedures and adaptive separation criteria will be highlighted.
- Symbolic conflict detection and resolution will be presented as an extension to the Flight Path Generator in an Expert System environment.

Need for a Flexible Flight Path Generator

A weak link of the optimized chain of operations that leads the aircraft from gates of the terminal area or holding points to the runway is the operation consisting of choosing a flight path for the initial approach phase.

Advantages of Standard Terminal Approach Routes

- *STAR*'s are precisely predefined and indexed.
- They make use of navigational aids.
- They can be flown by any aircraft and can even be flown automatically by aircraft equipped with advanced Automatic Flight Control Systems.

Limitations of *STAR*'s

- However *STAR*'s are too strict a framework to allow an efficient optimization of the airspace management.
- Aligning aircraft along one-dimensional paths does not take advantage of the three dimensions of the airspace to satisfy Separation Standards.
- Using *STAR*'s may arbitrarily limit the flow of aircraft that are allowed to approach the airport, though the runway capacity may not be reached.
- Besides, *STAR*'s do not allow the controller to meet the requirements of the pilots, in regard to the optimum flight conditions for a particular type of aircraft.

General Specifications

A Flight Path Generator would improve flow control procedures at busy airports. Unlike current use of *STAR*'s, a Flight Path Generator should

- Take advantage of the available airspace and of the various navigation capabilities of aircraft.
- Provide controllers with a choice of flexible candidate paths to guide aircraft to the runway and deliver them at the scheduled landing time.

Representation of Aircraft Motion in Space

The choice of a formalization of aircraft motion in space conditions the expressivity and the tractability of the representational framework in which aircraft trajectories are manipulated.

A representational framework derived from a State Space is introduced to address controllers' needs and to allow a symbolic manipulation of trajectories.

State Space Representation

- States are data structures giving snapshots of the current situation of the aircraft.
- Transitions between states are brought through the application of operators which operate on states.
- The goal is to find a sequence of operators which links two extreme states to build a trajectory leading the arriving aircraft to the runway.

Attractive Properties

- A level of abstraction is introduced to allow reasoning in terms of aircraft maneuvers, as they are planned by controllers or performed by pilots, rather than in terms of mathematical relations.
- Available operators correspond to feasible aircraft maneuvers, taking into account navigation and dynamic capabilities of the aircraft for which the trajectory is generated.
- Operators describe elementary kinematic actions such as a uniform move, a deceleration, and a turn.
- A trajectory is made of simple geometric figures which can be manipulated symbolically.
- This representation fit very closely with spatio-temporal common sense reasoning involved in the description of a feasible trajectory.

Heuristics to Construct Trajectories

Logic Programming Approach

- The declarative capabilities of Prolog, as a Logic programming language, are used.
- Operators are not functions transforming a state into another. They are declarative statements describing the logic of the problem.
- Operators impose constraints on parameters.
- An underlying propagation mechanism propagates the constraints.
- In consequence of Prolog's inherent inefficiency to deal with numerical values, new language primitives had to be defined to numerically solve numerical equations.

Pattern Instantiation

- The method used to build a trajectory is based on the use of a set of predefined flexible patterns that is incrementally instantiated.
- A pattern is a predefined trajectory type with several degrees of freedom. It can be viewed as a representative of a class or a family of trajectories with common properties.
- First, a pattern is chosen in accordance with a situation.
- Then degrees of freedom are incrementally fixed to satisfy the constraints imposed on the trajectory.

Example of a Pattern

Pattern: Axis_Trombone_Two_Speeds

- Aircraft converge and descend to the axis, defined as a vertical line from the touchdown end of the runway.
- They then diverge to the other side of the runway to follow a trombone-shaped figure to reach the outer marker.
- Deceleration occurs in two steps: once on the convergence to the axis; secondly on the downwind leg of the trombone.

A list of the operators for this pattern is now given:

```
Trajectory = [ Convergent_arrival,
               Convergent_ray_descent,
               Convergent_ray_deceleration_to_entry_speed,
               Convergent_uniform_move,
               Axial_turn,
               Divergent_ray_descent,
               Divergent_uniform_move,
               Turn_to_downwind,
               Downwind_first_uniform_move,
               Downwind_deceleration_to_final_approach_speed,
               Downwind_second_uniform_move,
               Downwind_third_uniform_move,
               Turn_to_base,
               Base_first_uniform_move,
               Base_second_uniform_move,
               Turn_to_intercept,
               Intercept_uniform_move,
               Turn_to_final,
               Final_uniform_move,
               Glide_slope_first_descent,
               Glide_slope_second_descent ]
```

Advantages of the Pattern Scheme

Expressive Power and Flexibility of Patterns through Examples

- Legs must have a minimum length corresponding to a given number of radar scans. The base leg, for instance, is composed of a uniform move during a fixed period of time, say thirty seconds, followed by a uniform move of arbitrary duration.

- Unlike current practice, an extension of the length of the glideslope is made possible to allow vertical separation around the outer marker.

  (Merging a slower aircraft on final approach behind a faster one results in a large gap at landing. However if the faster aircraft intercepts the glide slope at a higher altitude-than the slower one, they may approach their respective interception of the glide slope simultaneously and then glide down in the scheduled order with minimum separation during the descent, thereby improving the runway throughput.)

- Short straight-line segments have been inserted between the essential maneuvers to make the generated flight paths easier to fly by reducing pilot workload and to allow real-time adjustments so that conformance alerts may be avoided.

Airspace Management

- Patterns offer a practical means of satisfying airspace management requirements.

- They have to be designed in such a way that they fit, by their shape itself, in a global organization of airspace.

- Pattern description is an independent part of the Expert System. When new procedures are imposed, patterns can be changed at low cost to satisfy new requirements.

Present State of the Expert System

Input

- The present position and values of the kinematic parameters of the arriving aircraft.
- The scheduled landing time assigned by the sequencing process.
- A unique aircraft identifier, such as the flight number.
- The aircraft type.
- Specific maneuver characteristic required by the pilot.

Output

- A set of feasible trajectories.
- A choice of flight paths is provided to the controller in an interactive manner.
- The controller should be enabled to arbitrarily fix some degrees of freedom.
- Various feasible 4-D flight paths are constructed and drawn on the screen as long as the controller asks for alternative paths.

Real-Time Requirement

- It is necessary to generate a multiplicity of paths within the controller's decision time.
- The present version of the system is written in Prolog and run on TI Explorers.
- Generating the first trajectory requires twenty seconds.
- Alternative solutions require between five and twenty seconds depending on the modification.
- Clarity and ease of extension were given priority over time optimization.
- Relevant rule of thumb should be used to limit backtracking and gain speed.

Embedded Knowledge

The amount of knowledge embedded into the system could be divided into three categories with respect to how it is exploited by the system.

Operational Knowledge

The underlying machinery that actually builds trajectories in details, from pattern descriptions, is not apparent to the user. It may be decomposed into successive layers:

- Primitives to handle numerical computations.
- Equation solving methods.
- Sets of equations that contain the necessary knowledge about geometry and kinematics in a compiled form.

Descriptive Knowledge

- A library of patterns, describing a trajectory as a flexible sequence of operators. Controller's experience is implicitly compiled into pattern descriptions.
- A data base containing aircraft navigation capabilities and maneuver characteristics.

Empirical Rules

- Empirical rules have been given the priority over a model-based reasoning.
- Rules are used to direct the construction of the trajectory, choose a pattern and instantiate parameters.
- The rules do not formalize a routinely taught knowledge, but are rather pragmatic rules of thumb.
- Directing the construction of a trajectory by localized advices is amenable to rules. It does not require a global algorithm; rules may be easily changed to try different tactics.

Personalization

The data base of empirical rules should be segmented to allow different layers of knowledge.

General rules

- General rules are widely recognized and applicable.
- They should appear in all implementations of the Expert System.

Customized rules for each terminal area

- Location-dependent rules should integrate the expert system in the environment in which it is supposed into be working.
- The geographical environment of the airport, such as
  - inhabited areas or montains
  - the runway configuration
  - local winds

  should be taken into account as feasibility or differentiation criteria in the construction of the trajectories.

User-dependent rules

- User-dependent rules should adapt the Expert System to the individual controller's habits and personal techniques.
- Instances of the controller'spreferred patterns should be generated in priority.
- Though symbiosis is only a remote dream, personalized rules should make the team, controller/Expert System, all the more efficient.
- The assistant would perform a task that is expected and understood by the controller.

Tactical Corrections

- Patterns allow tactical corrections to be made to the plan to meet requirements in a changing world.
- Patterns available in the library were designed to minimize the need for replanning.
- Short time intervals are provided between maneuvers to absorb minor conformance leeways and avoid the accumulation of errors that would require replanning.

Replanning

- Changes in the assigned schedule and conformance alerts will inevitably involve replanning.
- Available patterns are extensible and may be stretched or shortened, thanks to several degrees of freedom, to adapt to a dynamically changing runway schedule.
- Rescheduling during the late phases of the approach is undesirable since flexibility in the plan is no longer possible, once all degrees of freedom have been previously fixed. At this point only tactical adaptive adjustments may provide leeways.
- I am now improving the internal structure of plans to make the modification of an existing plan easier.
- There is an efficiency trade-off: modifying the old plan vs. complete replanning.

Accommodation of the User's View of the World

The system generates trajectories in a given order that reflects an implicit notion of grading. Nevertheless, the controller using it may impose external constraints that fix degrees of freedom and short circuit the search. For example, the controller may decide to impose a downwind track.

Multiple Runways

The system can easily deal with multiple runways, since a runway position is like any other constraint imposed on a trajectory.

Development Tool

- Patterns are data that can be very easily changed. It takes one hour to add a new pattern to the data base and have it ready for testing.
- The system provides a very flexible environment to develop new trajectory patterns and to test them.
- Patterns are described in a uniform way and the underlying machinery deals with all the geometric and kinematic computations.

Integration into the Controllers' Routine

- **The system could be introduced and tested with minimal disruption of current practice.**
- **The controller should gradually get away from fixed *STAR*'s and take advantage of the new diversity of paths that are provided in an interactive manner.**

User Interface

- **A smart user interface is essential in the case of a real-time interaction with essentially visual information.**
- **A smart graphics display is indispensable.**
- **The controller should be able to display generated trajectories for different aircraft, simultaneously or alternately, and select among them.**

Responsibility Issue

- **In the scheme of automatic conflict detection, the human will be more than ever part of the loop.**
- **The controller should be responsible for visually checking that the set of displayed trajectory plans is actually conflict free.**
- **The Expert System plays the role of an assistant.**

Decision Making Process

- **The present system generates a sample of trajectories and enables the controller to impose external constraints.**
- **The system could also advise the controller.**
- **However, as soon as a direct interaction between a human decision-making process and a machine occurs, conflicts are imminent.**
- **The Expert System should generate a sample of conflict free paths and with all the elements in his hands, let the controller make the final decision.**

Conditions of Future Development of the Expert System

Additional Features are needed

The current program is a basis for a larger Expert System.

Collision Avoidance

- To make it applicable, the system should be extended to a multiple aircraft environment in order to deal with conflict detection and resolution.
- The system should provide the controller with not only feasible, but conflict free paths. (Current research)
- The system should take advantage of a symbolic representation of trajectories and reason qualitatively in terms of geometric concepts.
- This would allowanalyses of the nature of the conflict since the environment of the conflict is described.

Conformance Equipment

- New guidance and communication equipment is needed to enable pilots to fly the assigned paths.
- Committed trajectory descriptions, certified by the controller, have to be digitally uplinked to the aircraft.

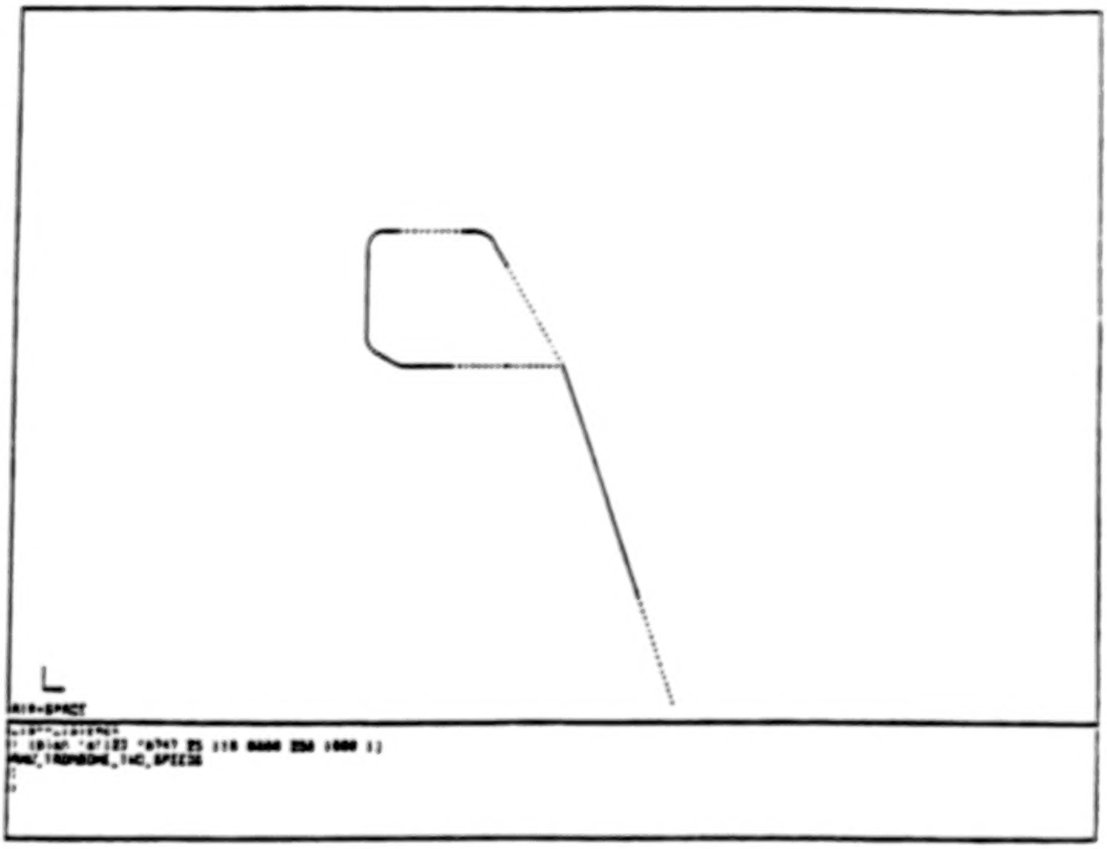

Figure 1. The following examples (figs. 1-6) show the variety of flight path plans that the present system can generate. Each path leads an aircraft from an initial state (terminal area entry point) to a final state (runway in center of screen). The dotted lines represent maneuvers (descent deceleration). The flexibility of each pattern is highlighted. Note the global shape of the trajectory and the maneuver phases. The assigned axis-altitude is 4000 feet. The distance between the downwind track and the runway is 6 nautical miles.

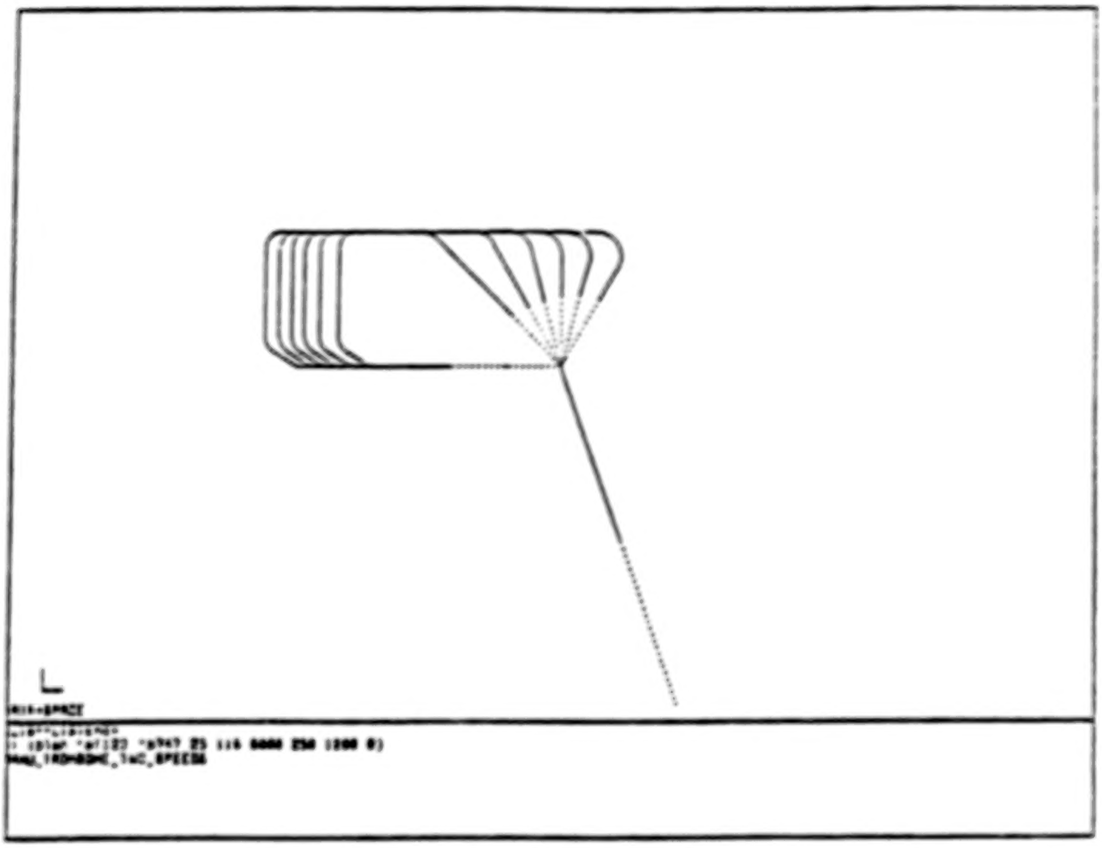

Figure 2. A more remote scheduled landing time allows more freedom in the replanning. Note the different directions of the divergent ray.

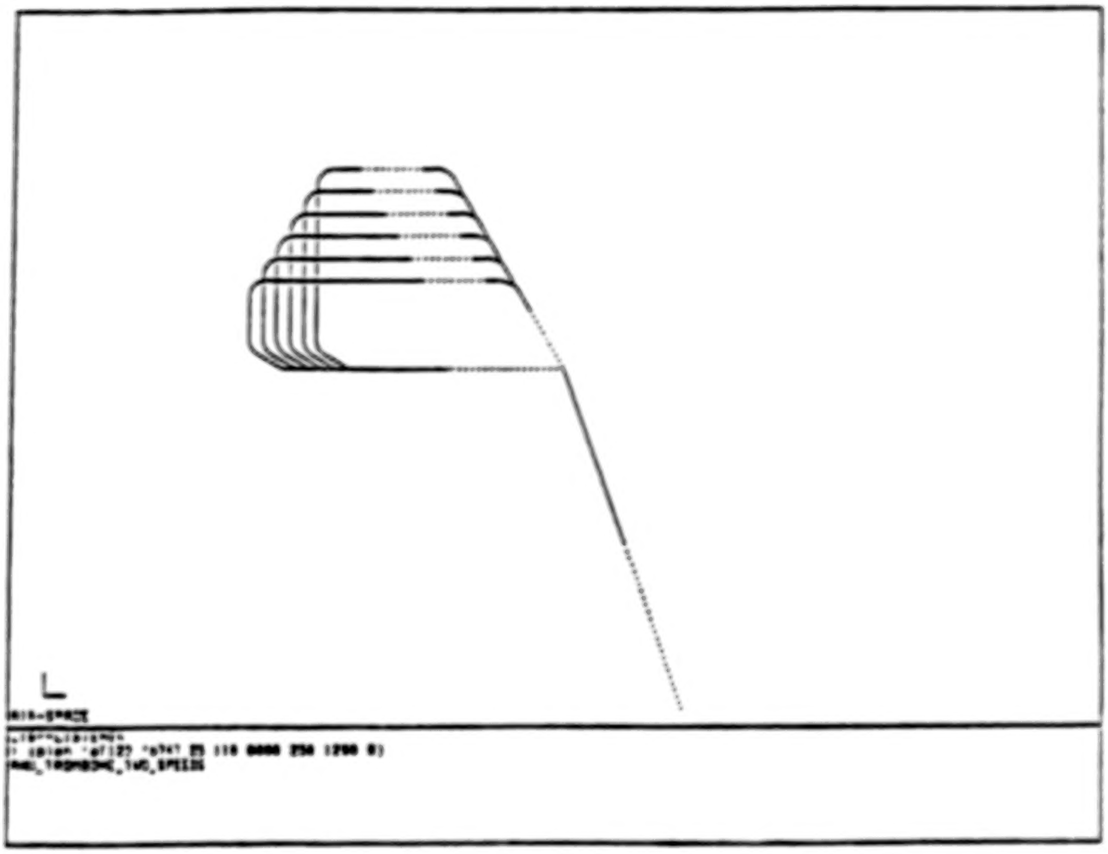

Figure 3. Note the different distances between the downwind leg and the runway.

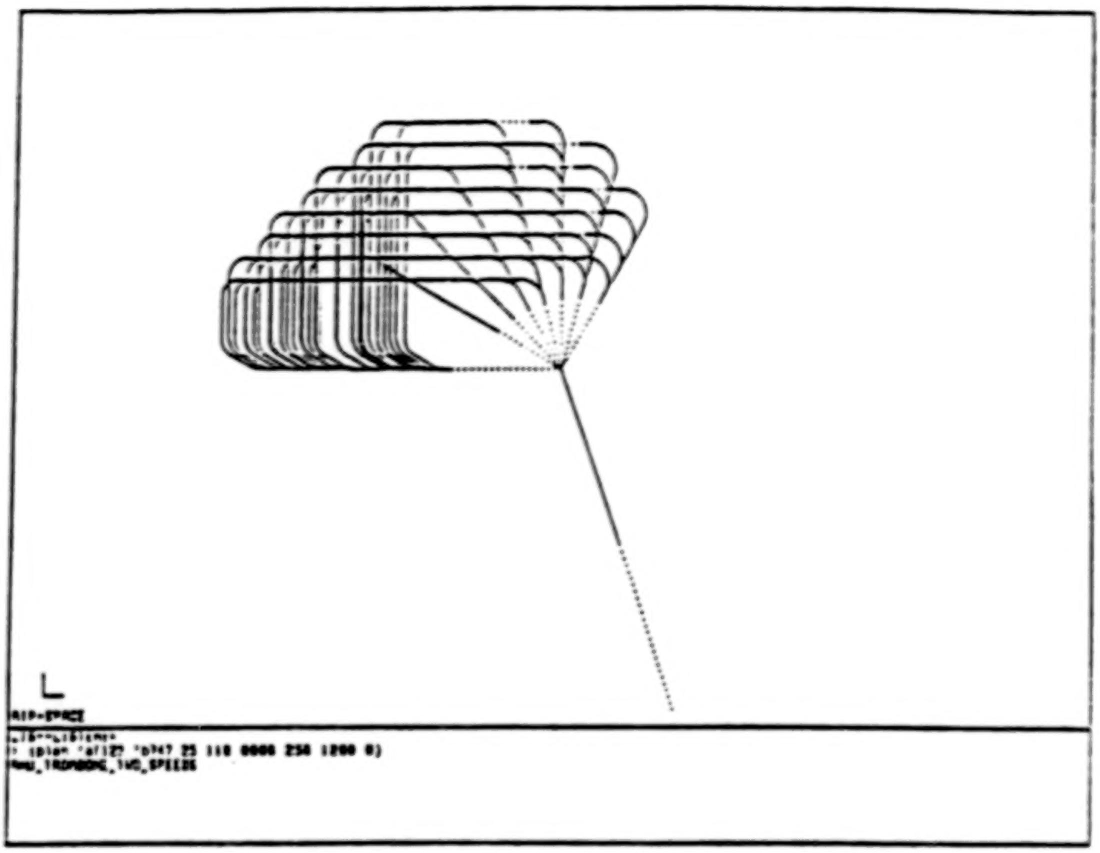

Figure 4. Note the various combinations of divergent ray directions and distances between the downwind leg and the runway. All of these paths precisely meet the same landing schedule.

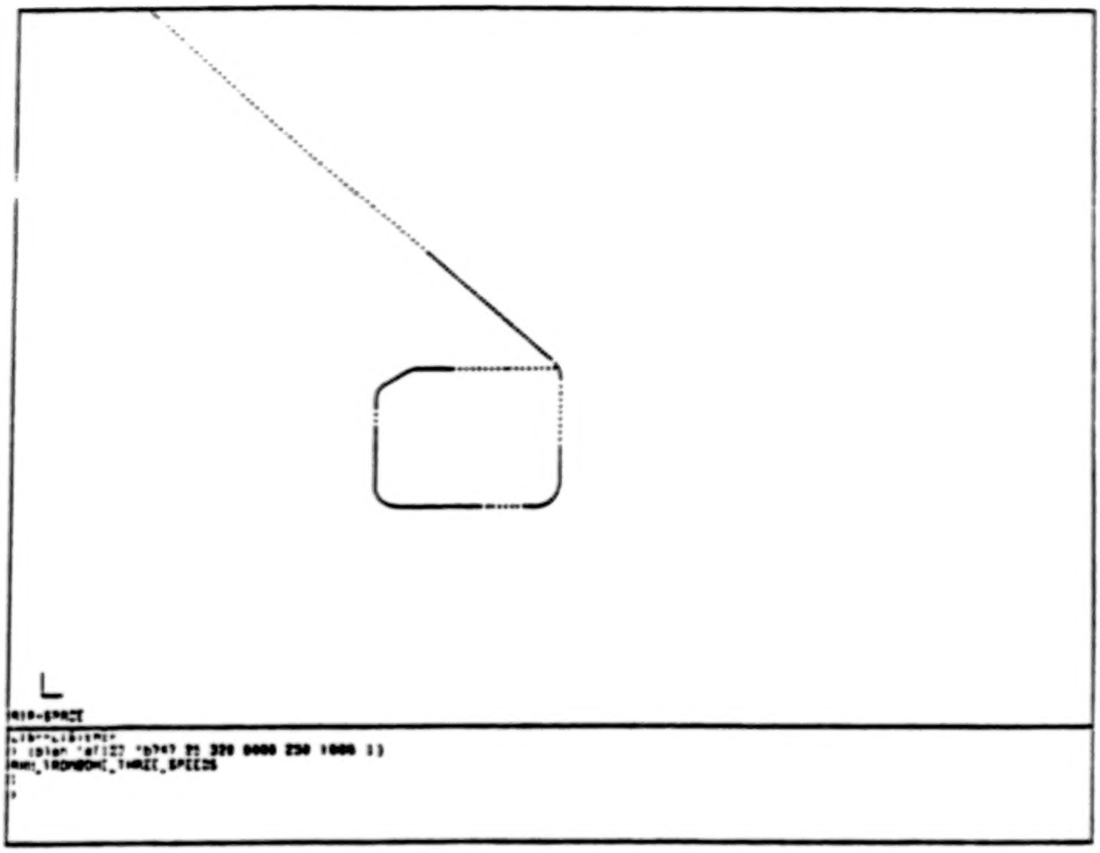

Figure 5. Note that aircraft may arrive from any direction.

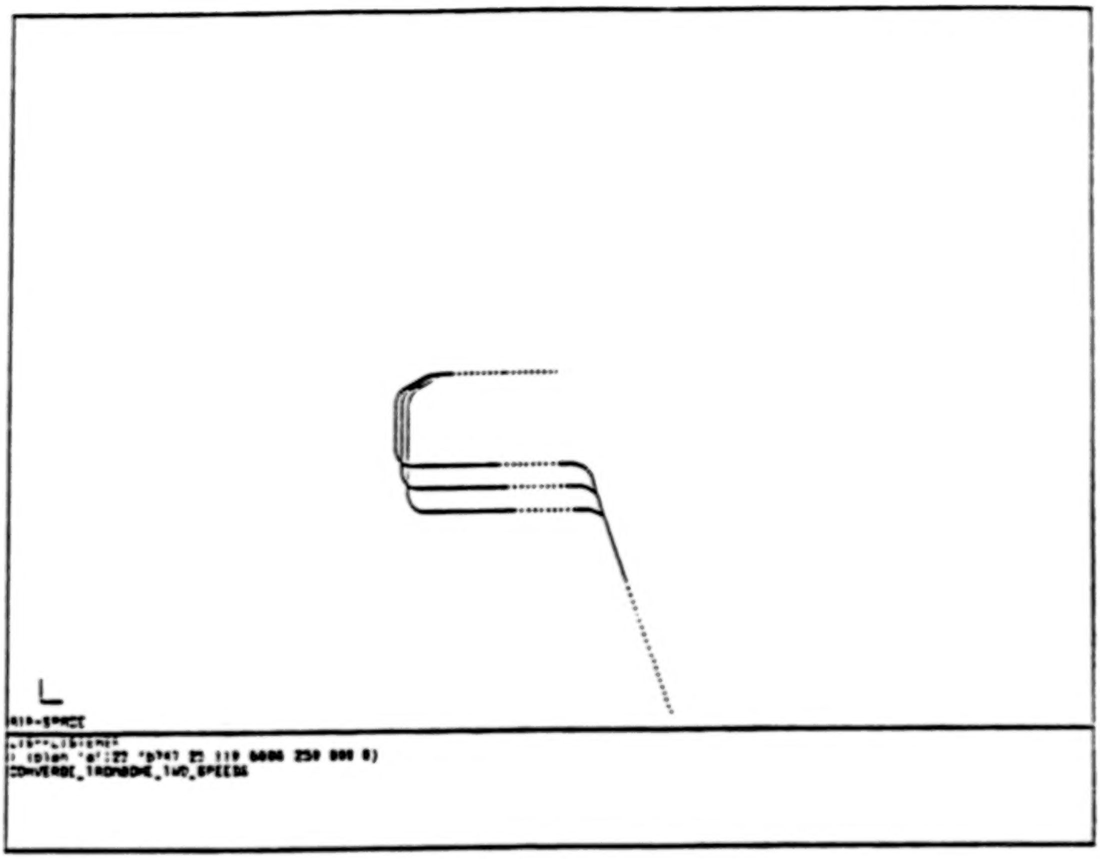

Figure 6. Note the different distances between the downwind leg and the runway.

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INVESTIGATION OF SURFACE WATER BEHAVIOR DURING GLAZE ICE ACCRETION

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ABSTRACT

A series of experimental investigations focused on isolating the primary factors which control the behavior of unfrozen surface water during glaze ice accretion were conducted. Detailed microvideo observations were made of glaze ice accretions on 1" diameter cylinders in a 6" square cross section closed-loop refrigerated wind tunnel. The tunnel was run at: a free stream velocity of 150 Kts; air temperature in the range of -9°C to -4°C; a nominal center line liquid water content between 0.7 g/m^3 and 1.2 g/m^3; and with a cloud droplet Mean Volumetric Diameter (MVD) of 30 microns. Distinct zones of surface water behavior were observed; a smooth wet zone in the stagnation region which had a uniform film of water; a rough zone where surface tension effects caused coalescence of surface water into stationary beads; and a zone where surface water ran back as rivulets. The location of the transition from the smooth to the rough zone was found to migrate with time towards the stagnation point. Comparative tests were conducted to study the effect of substrate thermal and roughness properties on ice accretions. The importance of surface water behavior was evaluated by adding a surfactant to the icing tunnel water supply. This reduced the water's surface tension and significantly altered the accreted glaze ice shape. Measurements were made to determine the temperature variation of the contact angle and hysteresis of water droplets on ice. The contact angle and hysteresis were found to increase sharply at temperatures just below 0°C. This explains the high resistance to motion of water beads observed on accreting glaze ice surfaces. Based on this investigation the importance of surface water behavior to the glaze ice accretion process was demonstrated. A simple multi-zone modification to the current glaze ice accretion model was proposed. The model incorporates discrete zones of surface water behavior, each with a characteristic surface roughness.

NOMENCLATURE

A = surface area, m^2
C_i = specific heat capacity of ice, J/kg K
C_p = specific heat capacity of air, J/kg K
C_w = specific heat capacity of water, J/kg K
D = diffusion coefficient of water vapor in air, m^2/s
F = force, kg m/s
h = local convective heat transfer coefficient, W/m^2 K
k = thermal conductivity of air, W/m K
L_f = latent heat of fusion of water, J/kg
L_s = latent heat of sublimation of water, J/kg
L_v = latent heat of vaporization of water, J/kg
$\dot{M}''$ = local mass flux/time, kg/m^{2}s
$\dot{Q}''$ = local heat flux/time, W/m^2
r = recovery factor, 0.875 (-)
T_{surf} = equilibrium surface temperature, °C
T_∞ = cloud temperature, °C
t = icing time, s
V_∞ = free stream velocity, m/s
W = cloud liquid water content, g/m^3
β = local collection efficiency (-)
$\Delta\theta$ = contact angle hysteresis, °
ΔT_∞ = cloud supercooling = T_∞ (°C)
θ = contact angle, °
θ_a = advancing contact angle, °
θ_r = receding contact angle, °
$\rho_{v,surf}$ = saturated vapor density over surface, kg/m^3
$\rho_{v,\infty}$ = saturated vapor density in cloud, kg/m^3
σ = surface tension, kg/m s^2

1. INTRODUCTION

The behavior of unfrozen water on an accreting glaze ice surface can, directly and indirectly, influence the shape of the resulting ice accretion. The surface transport behavior of the unfrozen water prior to freezing, has a direct impact on the ice shape due to its effect of redistributing the impinging water mass. The surface water behavior also indirectly influences the ice accretion through its impact on surface roughness which modifies the local convective heat transfer. The local heat transfer is the controlling factor in wet surface glaze ice accretion where the ice accretion rate is limited by the ability to remove latent heat of fusion from the surface.

Current ice accretion models ignore the specific details of unfrozen surface water behavior during glaze accretion. The surface transport behavior and surface roughness are both treated in a simplistic or heuristic manner. The simplistic evaluation of surface roughness and transport behavior which omits consideration of the surface physics is considered to be a contributing factor in the poor agreement between current glaze ice accretion models and experimental results[1].

This paper describes a series of experimental investigations focused on isolating the primary factors which control surface water behavior. The experimental investigations include: measurement of the contact angle and resistance to motion of water on an ice surface; photographic observations of surface roughness during glaze ice accretion on cylinders; differential comparison of substrate thermal and surface properties on ice accretion; and influence of the surface tension on glaze ice accretion. The results support the importance of surface water behavior to the icing process in the glaze ice regime. A simple modification to existing glaze ice models is also proposed.

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2. ICE ACCRETION MECHANISMS INFLUENCED BY SURFACE WATER BEHAVIOR

The primary ice accretion mechanisms which are influenced by the behavior of unfrozen surface water are the convective heat transfer, which is strongly related to the surface roughness[2], and the mass transfer at the surface which is partly determined by the water runback characteristics of the surface. Both the heat and mass transfer will be discussed briefly below in the context of ice accretion models to identify the importance of surface behavior on the ice accretion process.

2.1. Mass Transfer

The principal modes of liquid water mass transfer on an accreting ice surface are shown schematically in Fig. 1 which depicts mass flux into and out of a control volume at the ice surface. The primary source of liquid water is the impingement of supercooled droplets. The impinging liquid water mass flux $\dot{M}''_{imp}$ is linearly related to the ambient liquid water content W, the local droplet collection efficiency and the free stream velocity V_∞.

$$\dot{M}''_{imp} = \beta W V_\infty \qquad (1)$$

The double prime superscript is used to indicate that the quantity is defined per unit area of the icing surface.

Liquid water may also enter the control volume through mass flow along the surface ($\dot{M}_{in}$ in Fig. 1). Liquid water leaves the control volume through freezing at the ice water interface $\dot{M}''_{freeze}$, and surface flow out of the control volume $\dot{M}_{out}$. Some mass also leaves the control volume due to evaporation but this is generally small in the icing problem and will be neglected in the following analysis. The freezing mass flux $\dot{M}''_{freeze}$ is determined by the ability to convect the latent heat resulting from the water-ice phase transition away from the surface and will be discussed more fully in Section 2.2.

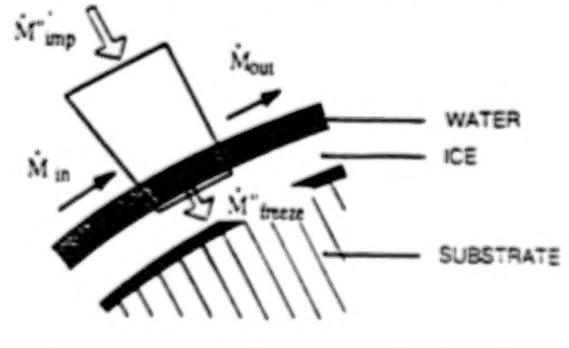

Fig. 1 Control volume mass balance for a wet ice surface.

In steady state, the liquid mass flux into and out of the control volume, **which has a surface area A, must balance**

$$A \cdot \dot{M}''_{imp} + \dot{M}_{in} = A \cdot \dot{M}''_{freeze} + \dot{M}_{out} \qquad (2)$$

For rime icing conditions, at cold temperatures, the convective heat transfer is sufficient to freeze all the impinging mass flux. In this case there is no surface flow and Eq. (2) reduces to:

$$\dot{M}''_{imp} = \dot{M}''_{freeze} \qquad (3)$$

In glaze icing conditions, there is insufficient heat transfer to freeze all of the impinging mass flux. In this case, the surface flow terms in Eq. (2) have to be considered. In current ice accretion models, all unfrozen water is assumed to run **back out of the control volume, while unfrozen water from** the next upstream element is assumed to flow into the control volume.

The assumption of uniform runback is quite reasonable for icing conditions where a thin water film covers the glaze ice surface. However, recent NASA high speed photographic studies indicate that other runback mechanisms may exist[3]. In some of the NASA studies surface water was observed to coalesce into beads which remained stationary on the accreting ice surface. An example is shown in Fig. 2. The liquid beads were often surrounded by regions of otherwise dry ice surfaces and no runback was observed. The NASA observations suggest two potential scenarios for surface water flow in the presence of water beads. In one scenario, the water beads will grow until the increased heat transfer from the rough surface becomes sufficient for the freezing mass flux to equal the impinging mass flux and any surface flow into the control volume. In this case no water would leave the control volume and Eq. (3) would reduce to:

$$A \cdot \dot{M}''_{freeze} = A \cdot \dot{M}''_{imp} + \dot{M}_{in} \qquad (4)$$

In the alternate scenario, the water beads would grow through coalescence and impingement until external dynamic pressure and shear forces caused the droplets to slide along or be torn from the surface. In this case it is unlikely that the drop would move into the next control volume and the assumption of surface flow continuity implicit in current mass balance models does not hold. This may explain experimental observations of reduced total ice accretion at temperatures near 0°C [4].

It should be noted that both scenarios described above may occur depending on the particular temperature and liquid water conditions. It should also be noted that uniform water films were also observed in the NASA experiments particularly near the stagnation region.

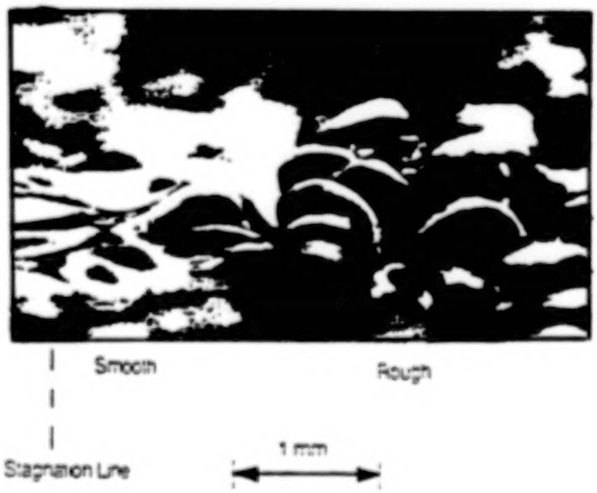

Fig. 2 Photograph of glaze ice surface (courtesy of William Olsen NASA Lewis Reserach Center).

2.2. Heat Transfer

The thermodynamic analysis presented in this paper for a surface accreting ice follows the earlier work by Messinger[5] and others[6,7] and is commonly employed in current ice accretion models[1,8]. The principal modes of energy transfer associated with the icing surface are depicted schematically in Fig. 3. Heat is added to the surface primarily from the latent heat of fusion released as the droplets freeze, but also from aerodynamic heating and, to an even smaller extent, from the kinetic energy of the droplets impacting the surface. Heat is removed from the surface primarily by convection, and to a lesser degree, by sublimation (when the surface is dry) or evaporation (when the surface is wet). In addition, heat is absorbed from the surface as the supercooled droplets impinge and warm to 0°C.

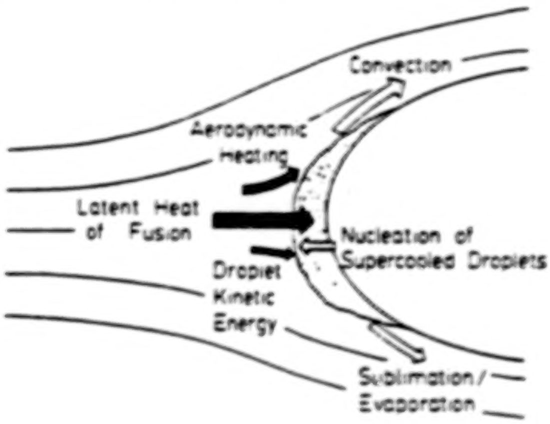

Fig. 3 Modes of energy transfer for an accreting ice surface.

The assumption of steady-state requires that the rate at which energy is added to the control volume equals the rate at which it is removed, i.e.,

$$\dot{Q}''_{in} = \dot{Q}''_{out} \qquad (5)$$

where $\dot{Q}''_{in}$ and $\dot{Q}''_{out}$ represent the energy added to and removed from, respectively, the control volume per unit area per unit time. Eq. (2) may be expanded into its component energy terms as

$$\dot{Q}''_{in} = \dot{Q}''_{freezing} + \dot{Q}''_{aero\ heating} + \dot{Q}''_{droplet\ kinetic\ energy} \qquad (6)$$

$$\dot{Q}''_{out} = \dot{Q}''_{conv} + \dot{Q}''_{sub/evap} + \dot{Q}''_{droplet\ warming} \qquad (7)$$

At steady-state it is assumed that the ice surface achieves a locally uniform equilibrium temperature, T_{surf}. Conduction into the ice is assumed to be zero and chordwise conduction between adjacent control volume is neglected. With these assumptions the component heat terms of Eqs. (6) and (7) may be written as

$$\left.\begin{aligned} \dot{Q}''_{freezing} &= \dot{M}''_{freeze}\,[L_f + C_i\,(0°C - T_{surf})] \\ \dot{Q}''_{aero\ heating} &= \frac{rh\,V_\infty^2}{2C_p} \\ \dot{Q}''_{droplet\ kinetic\ energy} &= \frac{\dot{M}''_{imp}\,V_\infty^2}{2} \end{aligned}\right\} \dot{Q}''_{in} \qquad (8a)$$

$$\left.\begin{aligned} \dot{Q}''_{conv} &= h\,(T_{surf} - T_\infty) \\ \dot{Q}''_{sub/evap} &= \frac{hDL}{k}(\rho_{v,surf} - \rho_{v,\infty}) \\ \dot{Q}''_{droplet\ warming} &= \dot{M}''_{imp}\,C_w\,\Delta T_\infty \end{aligned}\right\} \dot{Q}''_{out} \qquad (8b)$$

Note that both of the primary heat dissipation terms $\dot{Q}''_{conv}$, and $\dot{Q}''_{evap}$ contain the local convective heat transfer coefficient h. Also note that the $\dot{Q}''_{freezing}$ term which dominates the heat flux into the control volume, contains the freezing mass flux $\dot{M}''_{freeze}$. This implies that the local ice accretion rate is strongly coupled to the local convective heat transfer coefficient. For wet surfaces, the ice accretion rate is essentially limited only by the capability to transfer the latent heat of the freezing water away from the surface.

The convective heat transfer coefficient h is strongly dependent on the ambient surface roughness[2]. Current ice accretion models either empirically generate local convective heat transfer distributions to match natural ice shapes[8] or assume a uniform roughness and use integral boundary layer techniques to derive heat transfer distributions[9]. In these cases the surface roughness is characterized by an equivalent sand-grain roughness , which is is adjusted to match experimental ice accretions.

The surface water behavior is a primary factor in the evolution of roughness on an accreting glaze ice surface. The surface roughness determines the heat transfer behavior which ultimately determines the ice accretion rate under glaze conditions. Understanding the generation of surface roughness by the microphysical surface water behavior is a key component to understanding the glaze ice accretion process.

3. MICROPHYSICS OF SURFACE WATER BEHAVIOR

3.1. Forces Influencing Surface Water Behavior

The microphysical behavior of water on an aircraft surface is controlled primarily by the relative strength of the surface tension, aerodynamic and body forces. Surface tension forces tend to minimize the surface area of the fluid, causing the water to coalesce into beads or rivulets. They also act to oppose motion of fluid along the surface. Body forces such as gravity or centripetal acceleration act on the entire fluid bulk. Aerodynamic forces are due to pressure gradients and shear stress at the water-air interface.

3.2. Contact Angle

An important parameter in surface fluid behavior is the contact angle θ. It is defined in Fig. 4 as the angle the fluid-vapor interface makes with the underlying substrate. The nominal contact angle is a property of the specific gas-liquid-solid combination and may vary with temperature. The wettability, or tendency of a fluid to spread on a particular surface, is inversely related to the contact angle θ. In general, for contact angle values of less than 10° the surface is considered wettable.

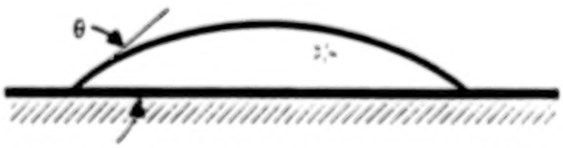

Fig. 4 Contact angle definition.

If the fluid is subject to an external force such as gravity, the contact angle may vary depending on the direction of the force relative to the contact line. This hysteresis effect can be visualized in the schematic view of a drop sliding down a vertical surface, shown in Fig. 5. On the lower surface of the drop the advancing line of contact causes an increase in the contact angle to its maximum allowable value, θ_a. Conversely, the receding edge of the drop remains at the lowest allowable value of the contact angle, θ_r. The contact angle hysteresis $\Delta\theta$ is the difference between the advancing and receding contact angles

$$\Delta\theta = \theta_a - \theta_r \qquad (9)$$

The contact angle hysteresis $\Delta\theta$ is a property of the specific gas-liquid-solid combination and will tend to increase with surface roughness. The resistance to motion of the liquid-solid line of contact can be related to the value of the nominal contact angle and its hysteresis[10]. In general, increasing values of θ and $\Delta\theta$ imply increased resistance to motion.

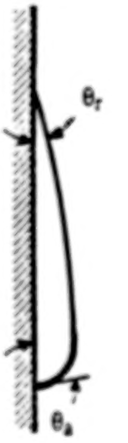

Fig. 5 Example of contact angle hysteresis in a droplet on vertical wall.

3.3. Modes of Surface Water Behavior

Water on an aircraft surface tends to behave in one of three distinct modes depending on the water flow rate, aerodynamic forces and the wettability of the surface. The three modes are shown in Fig. 6. For high water flow rates and wettable surfaces, the water will tend to coat the entire surface with a uniform water film. For lower flow rates, or higher contact angles, there is insufficient water to coat the entire surface. Once drying begins, surface tension forces will tend to coalesce the available water into either rivulets or water beads.

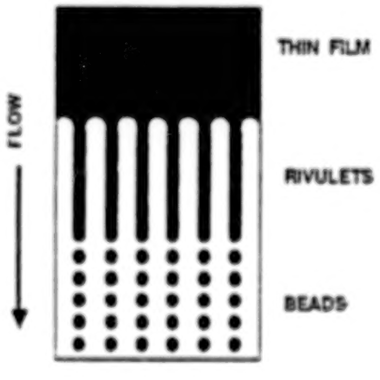

Fig. 6 Modes of water transport .

Water beads are generally associated with low flow rates or unwettable surfaces such as wax. Eq. (7) represents the overall force balance for a small stationary water bead. As long as the contact line force is greater than the sum of the aerodynamic and body forces, the bead will remain stationary.

$$\vec{F}_{contact} \geq \vec{F}_{aero} + \vec{F}_{body} \qquad (10)$$

The contact line force $\vec{F}_{contact}$ is the total force resulting from the contact line resistance to motion described in Section 3.2. Both the contact line force and the aerodynamic force are roughly proportional to the beads surface area, while the body force is proportional to the bead volume. This implies that, as the bead size is increased there will be maximum stationary bead volume for a given set of surface, flow and gravitational conditions.

4. MEASUREMENT OF CONTACT ANGLE BETWEEN ICE AND WATER

As discussed in Section 3, the contact angle θ and hysteresis $\Delta\theta$ are important parameters in the behavior of water on an ice surface. There is, however, very little data available on θ and $\Delta\theta$ for water on ice. This is partly due to experimental difficulties. Most investigations of the surface properties of supercooled water have concentrated on measurements of surface tension, σ[11]. In order to obtain preliminary working values of θ and $\Delta\theta$ for water on ice, a series of simple experiments were conducted.

4.1. Experimental Set-Up

The apparatus employed in these investigations is shown schematically in Fig. 7. A smooth layer of ice, approximately 8mm thick, was formed from distilled water on a metal plate which could be oriented at a variety of angles with respect to the horizontal. Pre-cooled droplets of distilled water were placed on the ice surface by a syringe and their shapes were recorded by a CCD Microvideo camera oriented to view the ice surface at a grazing angle. By use of a dark background and a diffuse light source, a sharp high-contrast image of the droplet at the ice-water interface could be obtained. This enabled contact angles to be measured to an accuracy of approximately ± 5°. The ice surface temperature was monitored by an Iron-Constantan thermocouple mounted in direct contact with the ice surface. The output of the thermocouple was presented on a digital display within the field of view of the video camera. This produced a simultaneous record of contact angle and surface temperature valid to approximately ± 1°C.

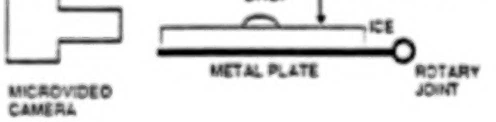

Fig. 7 Schematic of contact angle measurement set-up.

Measurement of the contact angle at various temperatures was obtained by initially cooling the iced metal plate, in a cold box, to a temperature below the target measurement temperature. The plate was then removed from the cold box and mounted horizontally within the field of view of the camera. As the plate warmed to the target temperature, droplets were placed on the surface and their shapes were recorded. Although the droplets would begin to freeze shortly after placement , the initial contact angle was preserved in the frozen drop and any transient effects could be observed in the video record. In this manner, values of the contact angle of water on ice could be obtained for subfreezing temperatures.

The contact angle hysteresis measurements were made utilizing a similar procedure. However, the iced plate was set to an angle of 30° with respect to the horizontal. Each droplet's volume was increased by syringe injection until motion began, at this instant the advancing and receding angles and the surface temperature were measured from the video recording.

4.2. Results

The observed dependance of contact angle θ and contact angle hysteresis $\Delta\theta$ with temperature are shown in Figs. 8 and 9 respectively. Due to the low values of contact angle at temperatures above -4°C, it was not possible to obtain accurate measurements above this temperature. However, at the freezing point (0°C) ice and water are in equilibrium so that the ice surface must be perfectly wettable, implying that both θ and $\Delta\theta$ must be zero. These points are included in the contact angle and contact angle hysteresis plots. They are consistent with the experimentally observed values and allow interpolation between -4°C and 0°C.

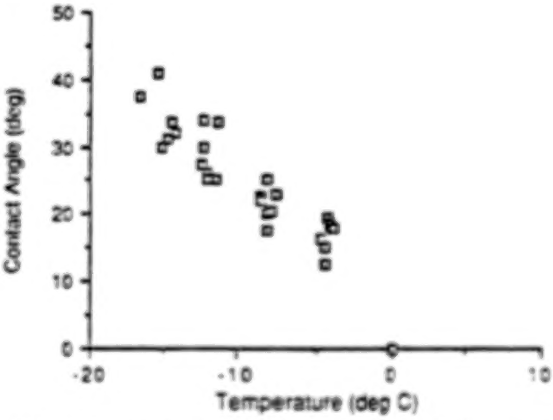

Fig. 8 Temperature variation for the contact angle for water on ice.

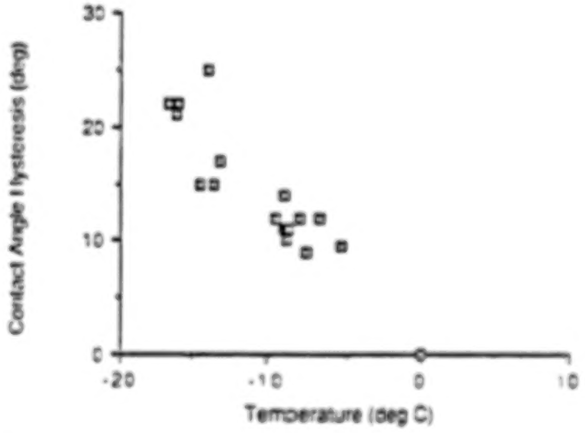

Fig. 9 Temperature variation for the contact angle hysteresis for water on ice.

Both the contact angle and hysteresis exhibit a strong variation with temperature particularly in the vicinity of the freezing point (0°C). These results imply that the wettability of the ice surface decreases greatly as the ice surface cools below freezing. For warm ice surfaces (near 0°C) water will tend to spread into thin films and the ice-water contact line will have a low resistance to motion. For colder ice temperatures, water will tend to bead into droplets which require a higher force to initiate fluid motion. In addition, a droplet freezing on a cold ice surface will have a greater roughness height than an equivalent volume droplet freezing on a warmer ice surface due to the increased contact angle at colder temperatures.

The strong temperature dependance of contact angle behavior indicates the potential importance of thermal gradients on the ice surface to the development of surface roughness. Small variations in surface temperature can restrict the mobility of water. This effect is thought to be the cause of the stable nature of the surface water beads observed by Olsen et al[3] and shown in Fig. 2. The dry ice surface around the beads can be cooled to temperatures well below 0°C by convective heat transfer. This cold dry surface therefore imposes a barrier to water flow away from the bead. Any impinging water which strikes the dry surface will quickly be frozen due to the low temperature. Any cloud droplets which strike the water will be trapped within the bead while ice is simultaneously formed underneath at the water ice interface. In this manner, the ice thickness can increase while the bead is observed to remain stationary.

5. EXPERIMENTAL OBSERVATIONS OF ICE SURFACE ROUGHNESS ON CYLINDERS

5.1. Experiment Set-Up

Detailed photographic observations of the behavior of surface water and formation of ice roughness on cylinders during glaze ice accretion were made in the Data Products of New England Icing Wind Tunnel. The experimental set-up is shown in Fig. 10. The tunnel was a closed-loop refrigerated system with a 6" square plexiglass test section. The test article was a cylinder which horizontally spanned the test section. Scale reference for the photographic studies was provided by a grid mounted on a thin splitter plate at the midplane of the test section. An 8mm CCD microvideo (camera A) with a macrolens for magnification was used to obtain a grazing angle view of the ice accretion. The camera was focused at the stagnation region near the center of the test section. An additional video camera (camera B) was mounted above and slightly upstream of the cylinder to provide a view of the ice accretion looking normal to the cylinder surface. Secondary lighting was provided to obtain a clear video record of the accreting ice surface.

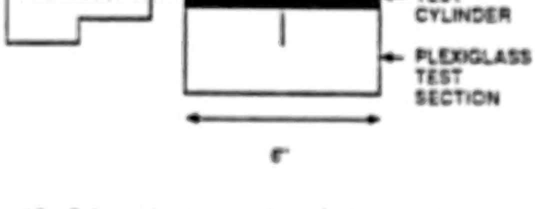

Fig. 10 Schematic cross section of wind tunnel set-up for ice roughness observations.

The tunnel and icing cloud parameters were set to yield a variety of glaze ice conditions. The air velocity was 150 kts for all tests. A range of free stream air temperatures between -9°C and -4°C was used. The center line liquid water content (W) was varied from $0.7 g/m^3$ to $1.2 g/m^3$. The icing cloud for the conditions had a nominal Mean Volumetric Diameter (MVD) of 30 microns. The standard exposure time was 3 minutes. The tunnel had previously been calibrated using an indirect method. There is, therefore, some uncertainty in the liquid water content and MVD values.

The liquid water content was observed to vary across the test section. This is apparent in Fig. 11 which shows the variation in ice thickness along the cylinder for a rime ice accretion. Photographic observations were therefore focused on the center line region where the ice deposit was uniform and the liquid water content calibration was valid.

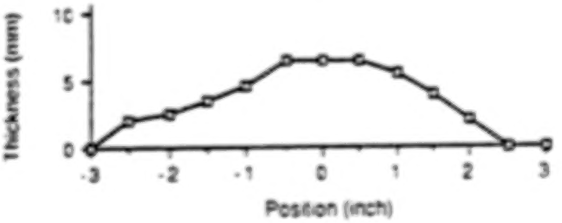

Fig. 11 Ice thickness variation across tunnel.

5.2. Results.

Fig. 12 shows two representative final glaze ice shapes for temperatures of - 9°C and - 4.5°C. During the ice accretion, three distinct types of ice surface behavior were observed, each having a characteristic roughness and identifiable boundaries. These were:

1. Smooth Zone

   Close to the stagnation point, during exposure to the icing cloud, the surface was observed by light reflection techniques to be uniformly wet with a thin film of water at warm temperatures. The surface in this regime was smooth, with no distinct roughness. The ice was translucent within this zone.

2. Rough Zone

   At some point downstream, there was a sudden transition to a significantly rougher surface. Within this zone, there appeared to be insufficient water to maintain a uniform film. Surface tension forces dominated the water surface behavior. Runback did not occur, rather, the water tended to coalesce into the water beads first observed by Olsen et al[3]. The scale length of the roughness was typically on the order of 1 mm. The transition between the rough and the smooth zones can be clearly seen in the gazing angle photograph shown in Fig. 2.

   Inasmuch as there was a distinct boundary between the smooth and rough zones this position could be easily identified on the grazing angle video recording. The angular position of this boundary is plotted in Fig. 13 for cold (- 9°C) and warm (- 4.5°C) conditions at a liquid water content of $1.0 g/m^3$. The boundary started at approximately 50° and propagated rapidly towards the stagnation region. The repeatable nature of the smooth-rough transition's propagation towards the stagnation region implies a clear underlying physical mechanism for the transition between the surface water behavior in the smooth and rough zones.

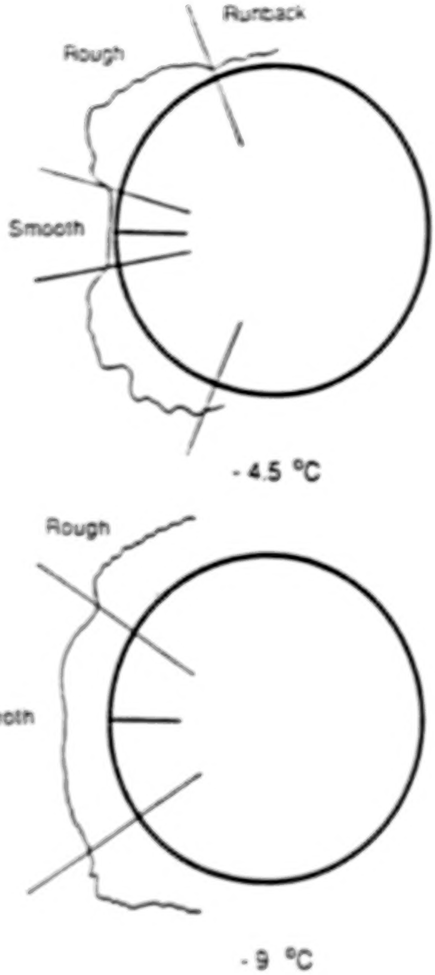

Fig. 12 Typical final glaze ice shapes showing distinct roughness zones.

   The ice accretion rate was observed to be enhanced in the rough zone as compared with the smooth zone. This can be seen in the ice profiles of Fig. 14 taken from the video at 30, 90 and 150 seconds after exposure to the icing cloud. The enhanced accretion rate is thought to be due to increased heat transfer resulting from the greater surface roughness in this zone. In all the cases observed in this study, the ice horns characteristic of glaze ice accretion were found within the rough zone.

3. Runback Zone

   At warm temperatures a third zone was observed aft of the rough zone. This region was characterized by areas of ice interspersed with uniced surface. This ice was observed to form during an initial transition period after cloud exposure. The ice was translucent, and quite often frozen rivulets could be discerned. In warm conditions and high liquid water contents, the surface water was observed to initially runback and then stagnate at the point of flow separation. This water then slowly froze as rivulets or as large coalesced water cells. Once ice began to form in the upstream rough zone, no additional surface water was supplied to the runback zone and the ice surface remained constant.

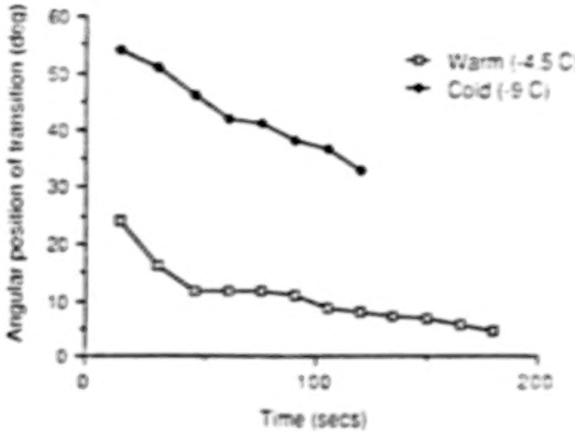

Fig. 13 Angular position versus time of smooth-rough transitions for two air temperatures.

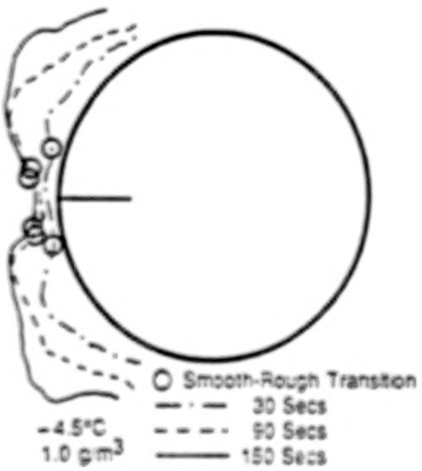

Fig. 14 Time development of glaze ice shapes.

6. EXPERIMENT TO DETERMINE THE EFFECT OF THE INITIAL UNICED SURFACE ON SURFACE WATER BEHAVIOR

6.1. Experimental Set-Up

The properties of the initial uniced surface that can affect the surface water behavior are:

1. Thermal characteristics
   (i.e: conductivity, specific heat capacity)

2. Roughness of the uniced surface

By exposing two test articles, identical except for either their thermal characteristics or initial surface roughness, to the same icing cloud it was possible to assess the individual importance of each parameter. Comparative tests of this type were carried out in the icing wind tunnel set-up described in Section 5. For these experiments, the test article was composed of two 3" long, 1" diameter cylinders of different material composition, separated by a splitter plate. As shown in Fig. 15 each half of the test article was viewed by a grazing angle microvideo camera (cameras A and C). A third camera (B) was mounted above and upstream of the article to simultaneously record the differences between the two cylinders.

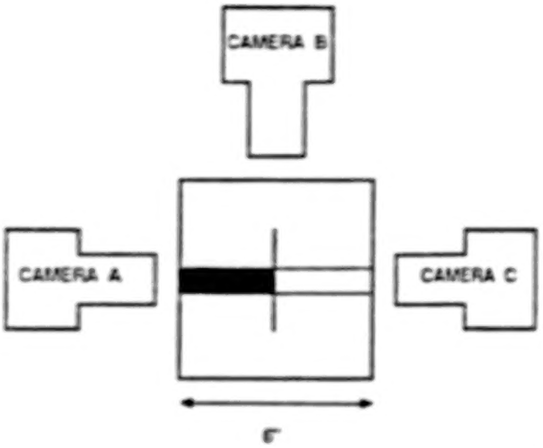

Fig. 15 Schematic cross section of wind tunnel set-up for uniced surface comparison tests.

Two cylinders were used in the thermal comparison experiments; a copper tube with a 1/16" wall thickness to investigate fast thermal response; **and a solid plexiglass rod to** investigate slow thermal response. To remove the possible influence of surface chemistry effects; each cylinder was covered with a single coat of acrylic paint.

For the roughness experiment, two cylinders were used. Both were manufactured from solid aluminum rods. One was extremely smooth with a polished finish obtained using '0000' emery paper. The rough cylinder had a repeatable surface pattern which was produced by knurling the cylinder on a lathe. The knurling process produces a pattern of trapezoidal surface elements, an example of which is shown in Fig. 16. For the cylinder used in these experiments the element had a height, h, of 0.8 mm, a width of 1 mm and a length of 2.7 mm.

The wind tunnel conditions were the same as those described in Section 5. The air temperature was varied between - 9°C and - 4°C, and liquid water content was between 0.7 g/m^3 and 1.2 g/m^3.

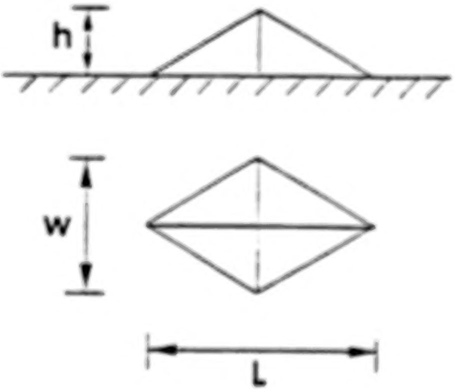

Fig. 16 Knurl roughness element definition.

6.2. Results

6.2.1. Thermal Comparison

Fig. 17 shows a typical comparison of the final ice shapes obtained after 3 minute exposure for the copper tube and the plexiglass rod. This comparison was run at a temperature of -5.5°C and a liquid water content of 0.95 g/m^3. The glaze ice horns on the copper cylinder were more sharply defined than on the plexiglass, which had a relatively flat front surface and was slightly thicker in the stagnation region. The angular position of the rough-smooth transition boundary is shown as a function of exposure time for these accretions in Fig. 18. For the plexiglass cylinder, the smooth zone shrinks much more rapidly than for the copper. The ice surface on the plexiglass cylinder became uniformly rough after 45 seconds of exposure. The enhanced roughness in the stagnation region, after this time, accounts for the thicker ice in the stagnation region and the relatively flat front ice surface observed in Fig. 17.

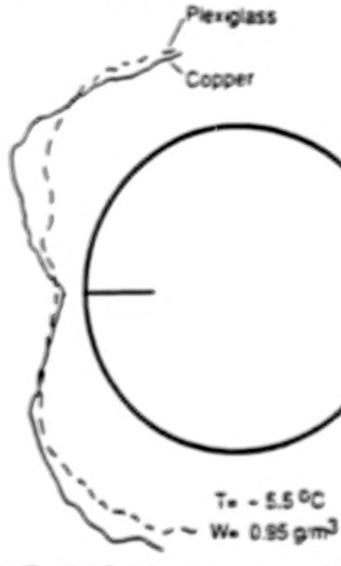

Fig. 17 Typical final ice shape comparison for copper and plexiglass cylinders.

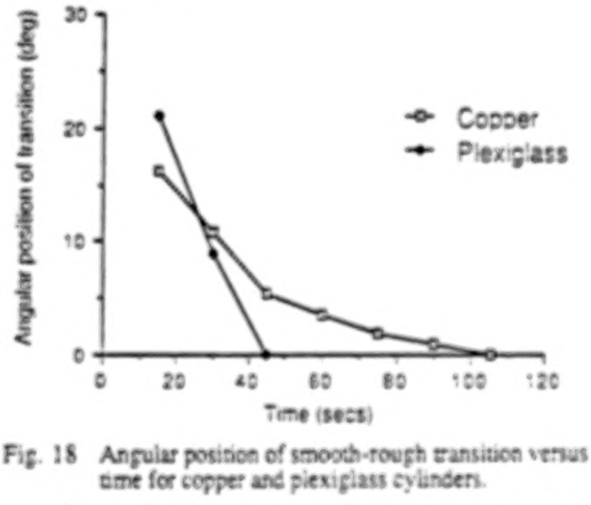

Fig. 18 Angular position of smooth-rough transition versus time for copper and plexiglass cylinders.

The water surface behavior after initial exposure to the icing cloud was observed to differ between the copper and plexiglass test articles. For the copper cylinder there was relatively little surface water flow prior to freezing and the initial ice surface was relatively smooth. For the plexiglass, droplet coalescence and runback were observed to occur prior to the initial ice formation. This resulted in a significantly rougher initial ice surface which is thought to be the cause of the difference in accretion behavior observed between the plexiglass and copper test articles.

In general, the differences in ice accretion behavior due to substrate thermal properties were observed to be most significant during the initial phase of ice accretion. As the accretion grows, the effect of initial conditions begins to wash out. After extended icing encounters the accretion will tend towards a shape which is controlled by the environmental parameters and is independent of substrate properties.

6.2.2. Uniced Surface Roughness

A typical comparison of final ice profiles for the polished (smooth) and knurled (rough) cylinders is shown in Fig. 19. The ice horns on the knurled cylinder were broader and further off the stagnation line than the horns on the polished cylinder. This is thought to be due to enhanced heat transfer in the horn regions during the initial phase of the ice accretion. A slight asymmetry is observed in the polished ice growth. This is thought to be due to the smooth surface on the polished cylinder which allowed gravitational forces to influence the initial mass flux, resulting in a larger ice horn on the lower surface.

The zones of smooth and rough ice growth discussed in Section 5 were observed in both the polished and knurled cases. Fig. 20 plots the angular position of the rough-smooth transition versus time. There is a significant difference between the two cases with the smooth zone being smaller for the knurled cylinder after approximately 80 seconds exposure time. An important observation was that the trapezoidal element pattern of the uniced knurled cylinder was clearly apparent in the ice accretion within the rough zone. This implies that the roughness geometry propagates in the ice accretion within the rough zone. In the absence of uniced surface roughness, water beading mechanisms appear to be the source elements for the roughness geometry

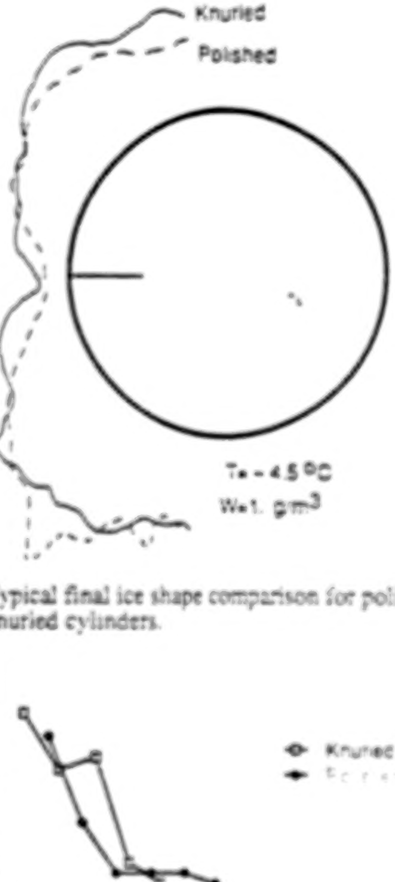

Fig. 19 Typical final ice shape comparison for polished and knurled cylinders.

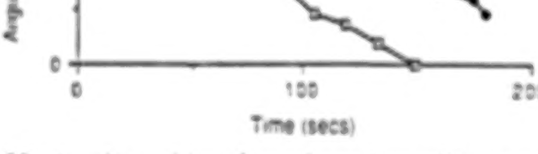

Fig. 20 Angular position of smooth-rough transition versus time for polished and knurled cylinders.

7. SURFACE TENSION EFFECTS ON ICE ACCRETION

7.1. Experimental Set-Up

The importance of surface water behavior was investigated by studying the effect of the surface tension of the water and studying the effect on the resulting ice accretion. The water surface tension was varied by the addition of a surfactant (Photoflo 200) which reduced the surface tension by approximately a factor of two while leaving its bulk properties (density, freezing temperature) unchanged.

The icing wind tunnel set-up was similar to that discussed in Section 5. Photoflo was added at a dilution of 1:200 to the icing cloud water supply. Icing tunnel conditions were matched as closely as possible between runs carried out with and without the surfactant added. Because the spray system was not specifically calibrated with Photoflo some uncertainty exists on liquid water content and MVD values. Based on splitter plate ice accretion this uncertainty is estimated to be on the order of 5%. Photoflo runs were conducted at a liquid water content of $1 g/m^3$ and for temperatures between -9°C and -4°C.

7.2. Results

Final glaze ice profile comparisons between normal icing cloud and the Photoflo modified cloud exposures are shown in Fig. 21 for the copper cylinder. The addition of Photoflo resulted in an opaque white ice with a smaller scale surface roughness and a significantly different profile. The horns were more pronounced and closer to the stagnation point. Fig. 22 shows Photoflo ice profiles for the copper cylinder at three values of temperature. At the lower temperature the glaze ice horn has become so pronounced that it no longer collected all the impinging water. A second horn was therefore able to develop behind it.

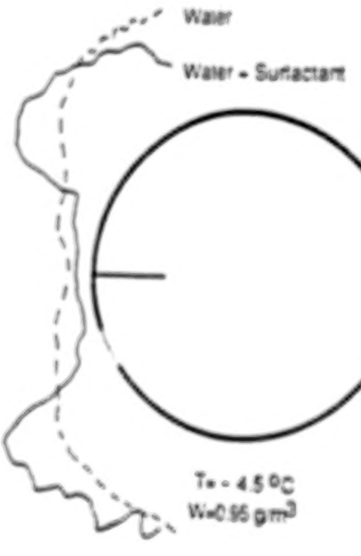

Fig. 21 Typical final ice shape comparison for cloud water supply with and without surfactant.

The different and unusual ice accretions obtained at reduced values of surface tension indicate that surface water behavior is indeed an important factor in the glaze ice accretion process and must be considered in physically realistic models.

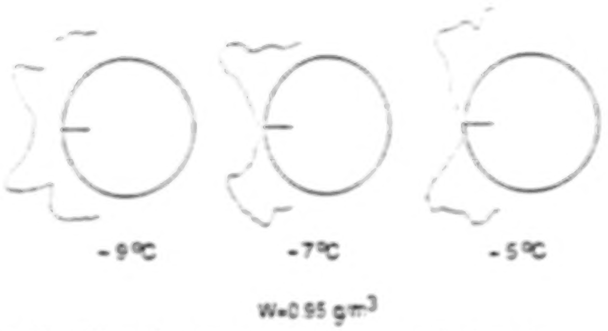

Fig. 22 Effect of air temperature variation on final ice shape with surfactant added to the cloud water.

8. IMPLICATIONS FOR ICE ACCRETION MODELING

Based on the observations of surface water behavior during glaze ice accretion, a relatively simple modification to the existing ice accretion model is proposed which may improve the current model's accuracy within the glaze ice regime. In this proposed "Multi-Zone" model, the accreting ice surface is divided into two or more discrete zones which have varying surface water behavior and surface roughness. This is in contrast to current techniques which assume the surface has uniform roughness and surface water runback.

In the simplest version of the model, the surface is divided into two zones. There is a smooth wet zone centered about the stagnation region where thin film runback occurs and the existing Messinger type models appear to be valid. In this region the heat transfer would be that for a smooth surface. The remaining ice surface would consists of a "rough" zone where surface tension effects dominate the surface water behavior and the characteristic water beads appear. The heat transfer within this region would be adjusted by incorporation of roughness correction factors appropriate to the bead dimensions.

The potential for improvement for a "Multi-Zone" model can be evaluated by considering the experimental and predicted ice accretions in Fig. 23, for a temperature of -4.5°C and a liquid water content of $1.1 g/m^3$. In this example, a single time step accretion was predicted using the "Lewice" code[9]. The code is seen to accurately predict the ice accretion in the stagnation region but underpredicts the accretion in the horns. The higher off stagnation heat transfer in the Multi-Zone model would increase the accretion in the horns and improve the

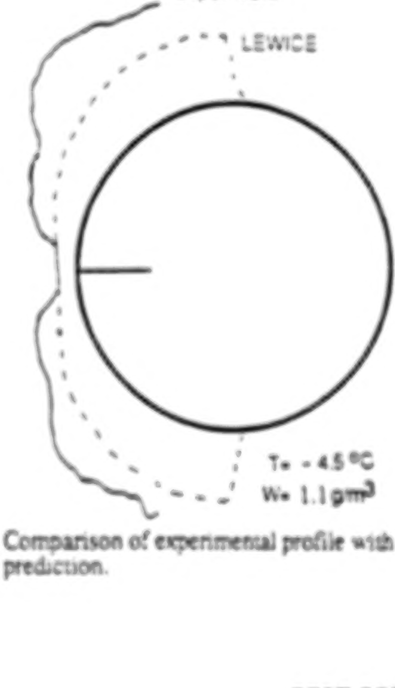

Fig. 23 Comparison of experimental profile with "LEWICE" prediction.

agreement with experiment. Two primary areas need to be addressed prior to implementation of a two zone model. They are, determining the smooth-rough transition locations and determining the appropriate value of equivalent sand grain roughness to be used in calculating the rough zone heat transfer coefficient.

The work described in Section 5 indicates that there are distinct physical mechanisms which control the position of the smooth-rough transition. However, further work is necessary to parametrically define the location of the smooth-rough transition. In addition, the factors which control the generation of roughness elements within the rough zone need to be investigated in the context of their impact on the local convective heat transfer coefficient.

9. CONCLUSIONS

The investigation of surface water behavior on an accreting glaze ice surface has shown the following:

1. Surfaces have been observed to have distinct zones of surface water behavior. They include: a smooth wet zone in the stagnation region where uniform film runback occurs; a rough zone where surface tension causes coalescence of the surface water into beads and no runback occurs; and a runback zone where surface water runs back as rivulets.
2. The location of the transition point between the smooth and rough zone was observed to propagate with time towards the stagnation point.
3. The freezing of the coalesced water beads in the rough zone generates a characteristic rough surface which enhances heat transfer.
4. Initial surface roughness patterns were observed to propagate in the accreted ice within the "rough zone".
5. Large variations in ice accretions were observed when the surface tension of the water was changed. This illustrates the importance of surface water behavior.
6. Measurement of contact angle and contact angle hysteresis for water on an ice surface showed a strong variation with the ice surface temperature. This temperature dependence indicates that thermal gradients along the ice surface may be important to surface water behavior and to the generation of roughness on an accreting ice surface.
7. Based on this investigation, a simple multiple zone modification to the current glaze ice accretion model is proposed. The model incorporates discrete zones of surface water behavior each with a characteristic surface roughness.

ACKNOWLEDGEMENTS

This work was supported by the National Aeronautics and Space Administration and the Federal Aviation Administration under Grants NAG-3-666 and NGL-22-009-640. Use of the icing wind tunnel facility was provided courtesy of Data Products of New England.

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OHIO UNIVERSITY

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INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT OHIO UNIVERSITY, 1987

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INTRODUCTORY REMARKS

The Joint University Program at Ohio University supported four important areas of research during 1987:

- Radio navigation using the NAVSTAR Global Positioning System (GPS) and the Long-Range Navigation system LORAN-C
- Weather data dissemination to aircraft
- Development of real-time hardware for the Digital Autonomous Terminal Access Communications (DATAC) data bus monitor
- Integrated avionics systems reliability performance

These efforts, mostly performed by graduate and undergraduate students, were highlighted by the announcement of two national awards: The Radio Technical Commission for Aeronautics William E. Jackson Award for the thesis "Error Sources Affecting Differential or Ground Monitored Operation of the NAVSTAR Global Positioning System" (ref. 1) and the Wild Goose Association Best Paper Award for the paper "Sole Means Navigation and Integrity through Hybrid LORAN-C and NAVSTAR GPS" (ref. 2).

A continuing effort has been under way in the evaluation of GPS and differential GPS for aircraft navigation. The 1987 research was focused on the error sources affecting differential or ground monitored GPS, including ephemeris, ionospheric, and tropospheric errors (refs. 1 and 3). The study involved both computer modeling and data collection to determine the effects of geometric decorrelation of the error sources as a function of the distance between a user and the reference station.

Work with both GPS and LORAN-C at Ohio University motivated the study of the use of LORAN-C to augment the GPS capability. This resulted in the development of concepts for a hybrid GPS/LORAN-C navigation service that has the capability to satisfy sole means navigation requirements for the continental United States (ref. 2). Results from this research were used for Congressman D. Smith's amendment to the Airport and Airway Improvement Bill (H.R. 2310). The amendment calls for closer synchronization of LORAN-C transmitters and initiates the development of requirements for a hybrid GPS/LORAN-C sole means of navigation.

An investigation is continuing on the use of automatic data transfer from ground stations to an airplane. Particular emphasis is on handling weather data. A specific goal is for the system to be extremely efficient principally because of the limited radio frequency spectrum available for such use and the tremendous amounts of weather data that will soon be available with the central weather processor and Next-Generation Weather Radar (NEXRAD) systems that are now being developed. During 1987, an experimental test bed was installed in an aircraft, capable of receiving and displaying color radar reflectivity patterns that were transmitted by a ground-based station. Current efforts are centered around the development of effective data compression techniques and utilization of existing radio frequencies in the aeronautical band.

A second version of the hardware for the DATAC bus monitor was completed. The hardware allows for real-time collection of all data transmitted over the DATAC bus, utilizing Direct Memory Access (DMA) techniques (ref. 4). Segments of bus data up to several seconds in length can now be stored for later use. This allows for analysis of the data when for instance a system malfunction occurs. The DATAC data bus is currently implemented at the Langley Research Center.

A parametric performance analysis for the NASA Langley Fault Inferring Nonlinear Detection System (FINDS) was conducted. FINDS is designated as a fault detection and isolation (FDI) algorithm to be used in conjunction with redundant sensor systems. The objective is to apply FDI techniques to reduce the number of redundant components while maintaining the same overall system reliability. Results from this study are documented in a Master's thesis (ref. 5). This work also led to a faculty internship at the Langley Research Center during which these techniques were further expanded (ref. 6).

This year has been very fruitful and beneficial to the participants of the program. Ohio University continues to feel strongly that the Joint University Program and engineering investigation are extremely valuable to its students who have the opportunity to become thoroughly involved with contemporary engineering.

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1. Sharma, S.: Error Sources Affecting Differential or Ground Monitored Operation of the NAVSTAR Global Positioning System. Ohio University, Department of Electrical Engineering, Master's thesis, June 1987.

   The concept of the differential GPS (DGPS) is similar to differential LORAN-C or differential Omega. A ground monitoring station determines GPS errors that are in common to the ground station and the user. These errors are broadcast to the users allowing them to increase their navigational accuracy to 5-10 meters. In addition to the instrument approaches being considered using DGPS, the DGPS also offers the necessary signal integrity, through monitoring provided by the ground station. This thesis describes the effects of geometric decorrelation caused by ionospheric and tropospheric propagation delays in detail. Both computer simulations and actual measurement data collection were performed to evaluate the errors sources affecting Differential or Ground Monitored operation of the NAVSTAR GPS.

2. Van Graas, F.: Sole Means Navigation and Integrity through Hybrid LORAN-C and NAVSTAR GPS. Proceedings of the WGA Technical Meeting, Rockville, Maryland, October 20-22, 1987.

   A minimum of four GPS range measurements or two LORAN-C Time Differences is normally required for a position solution for enroute navigation, area navigation, and nonprecision approaches. This paper describes a new technique that hybridizes GPS and LORAN-C used in the pseudorange mode to process efficiently all available navigation information. Emphasis is placed on combined GPS and LORAN-C timing, both for the ground/space facilities and the user.

   The hybrid system has the potential to solve the GPS and LORAN-C integrity and availability problems; more range measurements are available than required for the navigation solution.

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   This report describes the parameters and equations required to define an orbit around a planet, and to find the position of a satellite in the orbit at any desired time. As an example, Global Positioning System orbital parameters for the current baseline constellation are listed.

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   The Digital Autonomous Terminal Access Communications (DATAC) data bus is a new medium for the exchange of aircraft instrumentation data. DATAC is being developed by the Boeing Company and flight-tested by NASA Langley Research Center. Bus data evaluation and troubleshooting calls for a monitoring device that is capable of receiving and processing all DATAC bus data at operational bus speeds.

   This report describes the development and implementation of the DATAC Bus Monitor II, the Bus Monitor hardware interface board and preliminary software.

5. Alikiotis, D. A.: Flight Control Sensor System Parametric

Performance Analysis for the Fault Inferring Nonlinear Detection System (FINDS) Algorithm. Ohio University, Department of Electrical Engineering, Master's thesis, November 1987.

A parametric performance analysis for the NASA Fault Inferring Nonlinear Detection System (FINDS) is presented. FINDS is designated as a fault detection and isolation (FDI) algorithm to be used in conjunction with redundant sensor systems. The study is focused on multisensor, redundant flight control sensor systems to be used on jet transport aircraft and transatmospheric vehicles. The results point out the levels for each FDI probability (i.e. detection, isolation, false alarm, and damage) analyzed, that satisfy the NASA-set reliability requirements for the flight control sensor system configurations presented.

6. Hill, H. W., Jr.: Reliability and Performance of Multisensor Avionics Systems. Ohio University, Avionics Engineering Center, Report No. OU/AEC63-87TM NCC111/1 FR, December 1987.

Methods for dealing with combinatorial explosions in integrated avionics with FDI are summarized.

RELIABILITY AND PERFORMANCE OF MULTISENSOR AVIONICS SYSTEMS

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SUMMARY

In a previous work, Morrell and Motyka showed both the benefits of Fault Detection and Isolation (FDI) and also how Markov-chain techniques could be employed to analyze a fault-tolerant, redundant avionics system. The work described here was to use these concepts to develop an analytical tool for studying integrated avionics.

INTRODUCTION

In a pioneering work, Morrell and Motyka (ref. 1) applied Markov-chain techniques to analyze integrated avionics systems with Fault Detection and Isolation (FDI). Ohio University's task in this research area was to use these concepts to develop an analytical tool for studying integrated avionics. Need for such an analytical tool can be seen from figure 1. This figure highlights the major difficulty in employing Markov techniques to analyze large systems, that is, the problem of combinatorial explosion.

The point labelled 1 on the graph shows the unreasonably large amount of computer memory and computational effort involved in a "brute-force" implementation of Markov analysis, even for a system without FDI. The time required for a single iteration is seen to approach 10^{12} seconds. The storage requirements of about 1 terabyte (10^{12} bytes) are equally unreasonable. As indicated by points 2 and 3, there are conventional methods for dealing with combinatorial explosion, but the addition of FDI techniques (point 4) indicates that the addition of FDI once more makes the problem intractable by conventional solution means. A technique developed in this research project called Modular Computation (illustrated by point 5 in figure 1) does appear to make analysis of integrated avionics systems practical. However, some limitations must be made on the FDI schemes in order for this modular scheme to work. In particular, the FDI scheme cannot use information about one sensor set to determine the status of another sensor set.

APPROACH

Markov-chain techniques require a matrix multiplication for each time step. This is not as computationally intensive as it may seem, because the time steps can be chosen to be geometric (the penalty involved with geometric steps is in squaring a matrix, rather than multiplying a matrix by a scalar). The real problem is in the size of the matrix that must be used. The dimensions of this square matrix are equal to the number of system states that must be distinguished. Conventional techniques minimize this by grouping similar states together (represented by point 2 in figure 1) and by merging different failed states (point 3). Similar states are defined as those with the same numbers of components working and failed; e.g., 3 good gyros, 1 bad gyro & 4 good accelerometers. These techniques are inadequate for systems with FDI because there are four states for each component, instead of two: the actual condition of each component, and its diagnosed condition (which are not necessarily the same!) must both be kept track of. Figures 2 and 3 illustrate these differences.

The term Modular Computation was coined to describe a method of attacking Markov analysis of integrated avionics systems with FDI. Instead of having a "global" state-transition matrix and state vector containing the probabilities of every component group being in every possible state, a separate matrix and state vector are formed for each redundant sensor set. In this modular approach, results of multiplying the separate matrices and state vectors are combined with logic to produce the same result. Figures 4 and 5 show a schematic comparison of the two methods.

The method produces a considerable saving in iteration time and storage requirements (see point 5 in figure 1) because failure modes of the various sensor sets have been assumed to be independent. Typically this is a good assumption, but the presence of common-mode failures will limit the applicability of the modular approach.

Using this approach, a prototype numerical tool was developed in FORTRAN77 so that specifications and requirements for an FDI system could be developed. Preliminary results indicate that the tool works and that the approach is fruitful. Some features of the software tool are: (1) Inclusion of redundant state probability calculations to track round-off errors; (2) inclusion of false-alarm healing to evaluate its importance; (3) inclusion of error correction to evaluate its importance, and (4) differentiation of "undetected failure" and "detected failure" states.

FUTURE WORK

The work to date has only begun to explore several facets of fault-tolerant avionics; only two sensor types (gyros and accelerometers) have been included so far. The next step is to complete the Markov model for an entire integrated avionics system. Next, separate reliability studies should be undertaken for flight control, navigation, and weapons delivery. Additional parametric studies should be done of sensor scan rate and redundancy levels. The trade-off between false alarms and missed detections should be studied. Particularly for aerospace-plane applications, an investigation should be made of performance during flight-regime transitions. Finally, the limits of modular computation with "global" FDI should be studied.

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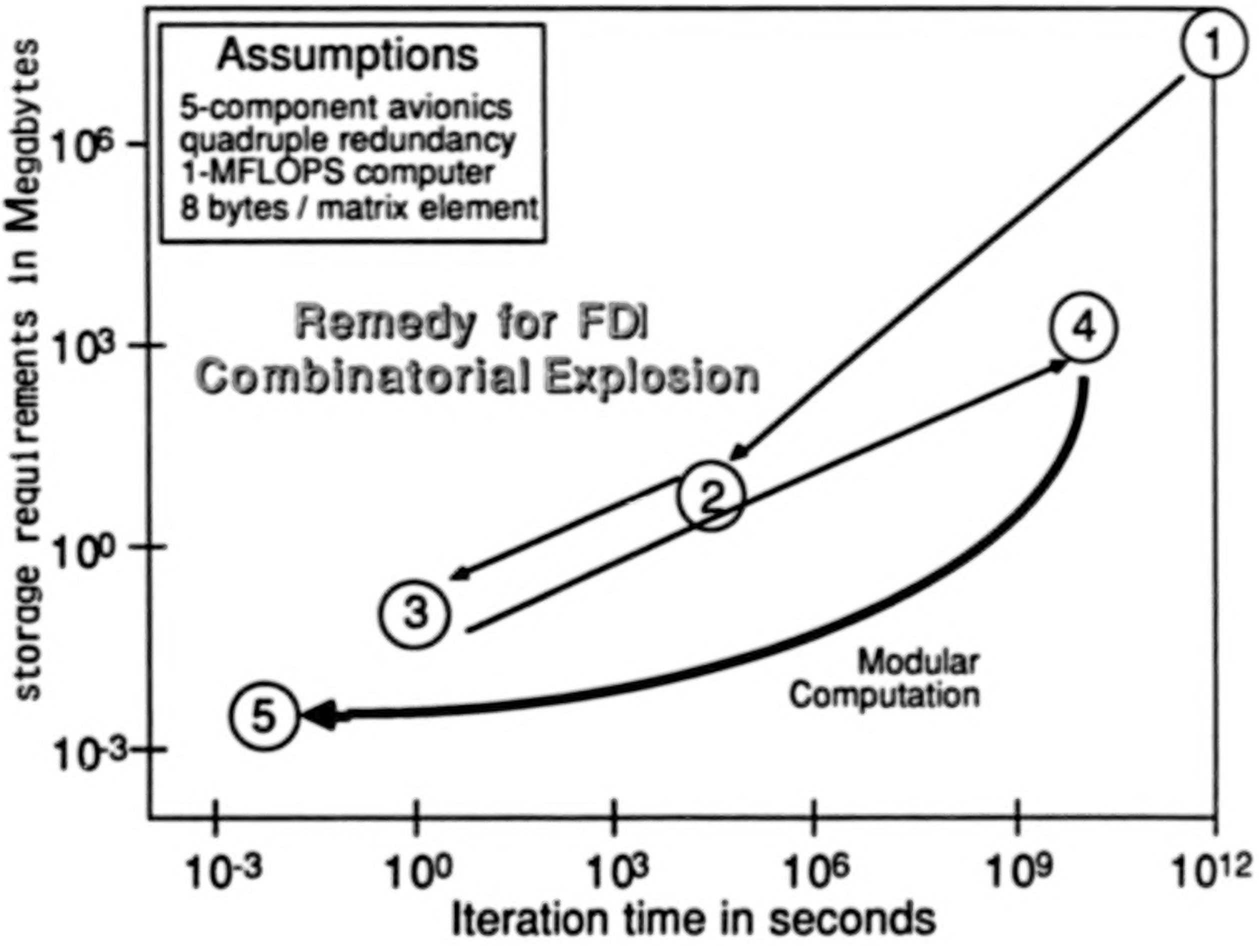

Figure 1. Combinatorial explosion and coping techniques.

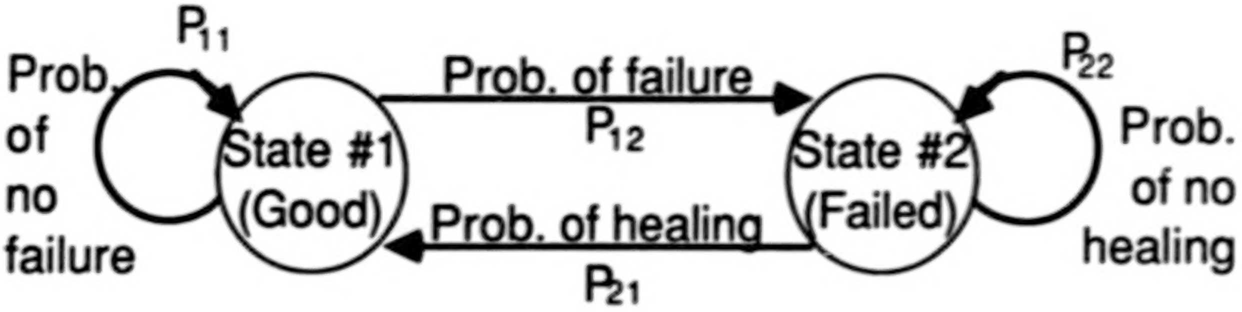
P11
Prob. of no failure
Prob. of failure
P12
State #1 (Good)
State #2 (Failed)
Prob. of healing
P21
P22
Prob. of no healing

Figure 2. Single-component states in conventional Markov analysis.

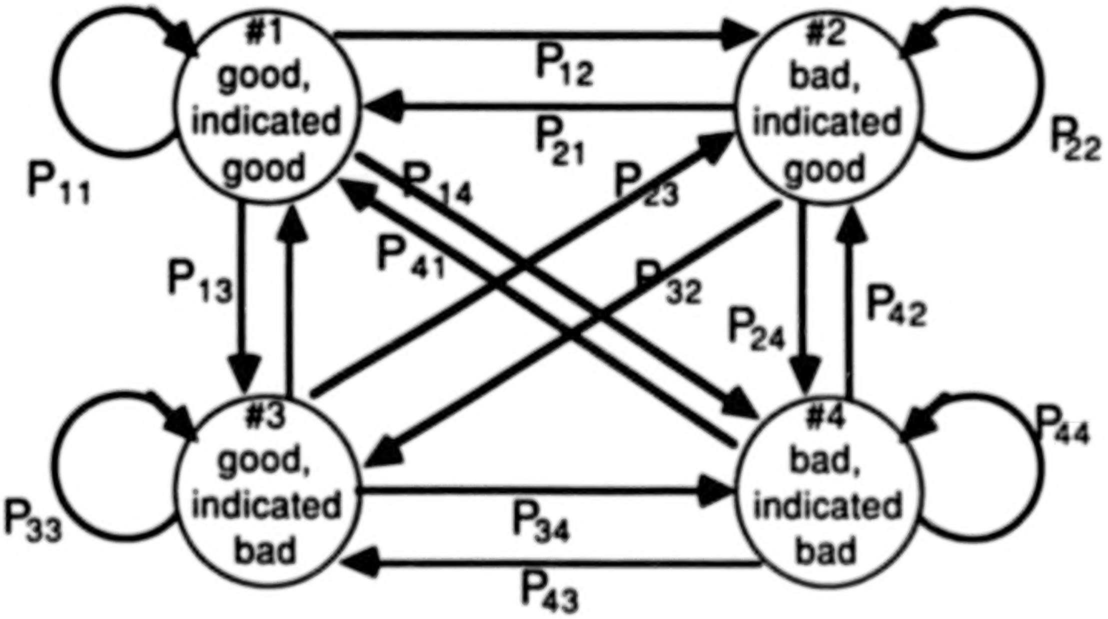
#1 good, indicated good
#2 bad, indicated good
#3 good, indicated bad
#4 bad, indicated bad
P11
P12
P21
P22
P14
P23
P41
P32
P13
P24
P42
P33
P34
P43
P44

Figure 3. Single-component states with FDI.

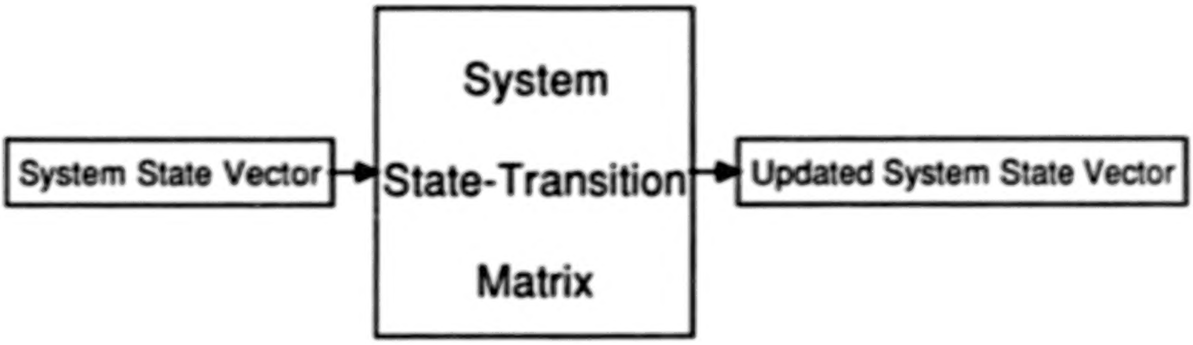
System State Vector
System
State-Transition
Matrix
Updated System State Vector

Figure 4. Conventional technique for updating the state vector.

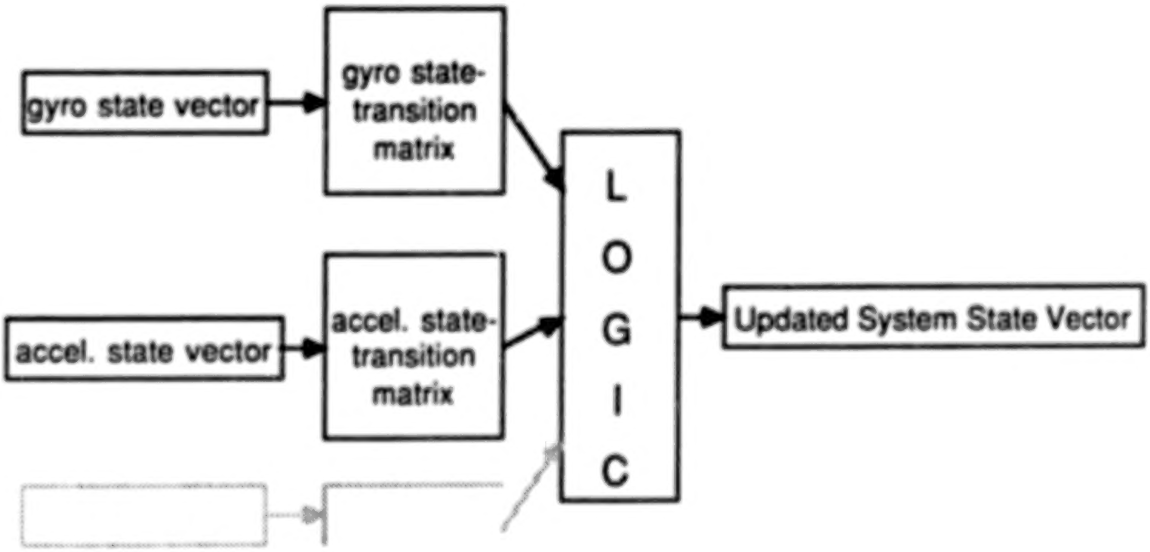
gyro state vector
gyro state-
transition
matrix
accel. state vector
accel. state-
transition
matrix
L
O
G
I
C
Updated System State Vector

Figure 5. Modular technique for updating the state vector.

INTEROPERABILITY OF NAVSTAR GPS AND LORAN-C

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SUMMARY

The NAVSTAR Global Positioning System (GPS), a satellite based radio navigation system, is expected to become operational around 1991. At that time, given the currently planned 21 satellite constellation, GPS will only qualify for a supplemental type certification. GPS does not fulfill the integrity and availability requirements for a sole means air navigation system for use within the National Airspace System.

Several schemes have been proposed to solve the GPS integrity and availability problems. This paper presents a new technique, developed under the Joint University Program, that is based on a hybrid system consisting of GPS and the Long Range Navigation system LORAN-C to fulfill the requirements of a next generation sole means air navigation system. In addition, the hybrid system will provide dissimilar redundancy: GPS and LORAN-C operate at different frequencies, each affected by completely different propagation anomalies.

A GPS/LORAN-C system for in-flight evaluation of hybrid navigation system concepts is currently being developed at Ohio University.

BACKGROUND

Current radio navigation systems are not sufficient to meet the future requirements for air navigation throughout the continental United States (CONUS). Air Traffic Control (ATC) necessitates an accurate positioning service that will be available virtually 100% of the time. This will likely occur in combination with an Automatic Dependent Surveillance (ADS) system to eliminate "blunders" and to improve the knowledge about the location of airplanes at any altitude within the National Airspace System. In addition, safety standards call for system unreliability numbers of less than one part in ten million and also require system integrity. Integrity is the capability to detect and warn the user that the system performance is outside some preset accuracy bound.

A few systems are currently in use that may be used as sole means navigation systems in controlled airspace. This means that no other system is required for the navigation function. Civil sole means navigation systems for CONUS are based on the Very High Frequency Omnidirectional Range (VOR) system and Distance Measuring Equipment (DME). Navigation systems that do not qualify for sole means but that may be used in combination with a sole means system are supplemental type systems. Examples of supplemental type systems are Omega, Non-Directional Beacons (NDB), and the Long Range Navigation system LORAN-C.

The NAVSTAR Global Positioning System (GPS) is a radio navigation system currently under development by the Department of Defense (DoD). When GPS becomes operational around 1991, it will only be certified as a supplemental type navigation system. GPS lacks sufficient integrity, and the planned 21 satellite constellation will only provide an availability of 98%, or approximately one week of outage during a year of operation.

Since GPS is considered to be the replacement for VOR and DME, several techniques have been proposed that improve the GPS performance in the areas of availability and integrity. These techniques include the addition of GPS satellites, ground monitors with geostationary satellites for dissemination of a GPS integrity message, and differential GPS.

Ground monitors will be able to determine satellite failures and therefore can generate an integrity message; however, the availability problem is not solved.

Differential GPS is capable of correcting for so-called "soft" GPS errors such as might result from satellite clock degradation. This will improve system availability somewhat, but will still not correct for total satellite failures.

Additional GPS satellites could satisfy the requirements. The main disadvantage of this approach is the cost related to the deployment of these satellites. The combined manufacturing and launch costs of one GPS satellite total approximately one hundred million dollars. The expected lifetime of a satellite is estimated to be 7.5 years. Even though some of the additional satellites might be necessary to satisfy the DoD operational requirements, it is expected that the civil availability requirements will dictate more satellites than the number required by the DoD. In addition, civil requirements indicate a need for dissimilar redundancy which can only be attained by a navigation system mix.

Another way to fulfill the integrity and availability requirements and also achieve dissimilar redundancy is by combining navigation systems. This paper is concerned with a new technique that hybridizes GPS and LORAN-C used in the ranging mode of operation. The hybrid system has the potential to meet both the availability and the integrity requirements for a sole means navigation system. In addition, it is expected that the requirements for nonprecision approaches will be fulfilled.

GPS/LORAN-C INTEROPERABILITY CONCEPTS

Concepts for a hybrid GPS/LORAN-C navigation system were developed during 1987 and are summarized (ref. 1):

- The functional block diagram of a hybrid GPS/LORAN-C system is given in figure 1. Except for the radio frequency (RF) circuitry, both systems share all functional sub-systems including the frequency reference source, the receiver processor, the random navigation (RNAV) calculations, and the user interface.

- The hybrid system should have test inputs with signals generated by the receiver/processor. The purpose of these test inputs is two-fold: receiver hardware delay calibration and receiver functional integrity.

- LORAN-C should be used in the pseudorange mode of operation. This will allow the hybrid system to process the LORAN-C signals in a manner very similar to GPS and will also take advantage of the LORAN-C clock information.

- The hybrid navigation solution should be implemented using a partitioned filter to avoid numerical instabilities and unpredictable failure modes.

At the same time, recommendations were developed to improve the navigation and timing capabilities offered by the LORAN-C system (ref. 1). It is recommended to implement time of transmission control for all LORAN-C stations under the condition that the impact on current users will be minimal. Otherwise, GPS receivers should be installed at each LORAN-C station to determine the station clock offset with respect to GPS. These offsets should be transmitted to the users using blink codes or additional pulses. This would establish, in essence, time of transmission control without affecting current users. Either timing option would significantly increase the LORAN-C coverage area and also result in navigational accuracies better than 250 meters (95%) throughout CONUS (ref. 1).

To predict LORAN-C pseudorange coverage, a computer program was developed. The current program predicts pseudorange coverage accounting for geometry and signal-to-noise ratio at the receiver. Figure 2 illustrates the predicted four-fold coverage of LORAN-C used in the pseudorange mode of operation. The coverage was computed under the assumption that all transmitters are synchronized. Note that the four mid-continent transmitters, indicated by triangles, are included in the calculations. These transmitters are scheduled to be operational by 1990. From figure 2 it follows that redundant coverage is available throughout almost all of the continental United States.

FUTURE RESEARCH

Based on the results obtained from the research described above, a generic hybrid GPS/LORAN-C receiver test bed is being developed. The receiver test bed will be installed in the Avionics Engineering Center's Dakota DC-3 N7AP for in-flight evaluation of the system. Aircraft data will be referenced to the measured positions obtained from a theodolite/mini-ranger ground tracking system. The data will be post-processed on the ground to verify the interoperability concepts.

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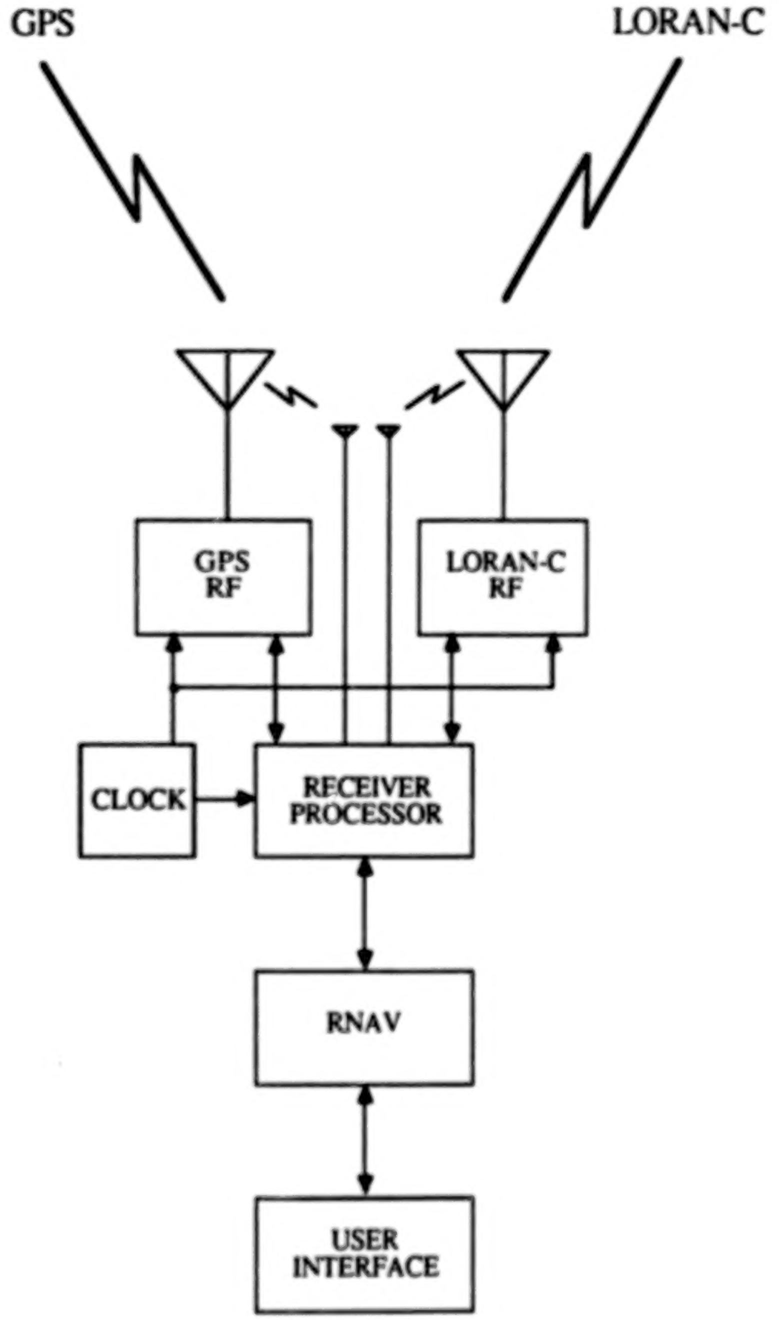
GPS
LORAN-C
GPS RF
LORAN-C RF
CLOCK
RECEIVER PROCESSOR
RNAV
USER INTERFACE

Figure 1. Hybrid GPS/LORAN-C functional block diagram with test inputs for receiver functional integrity and hardware delay calibration.

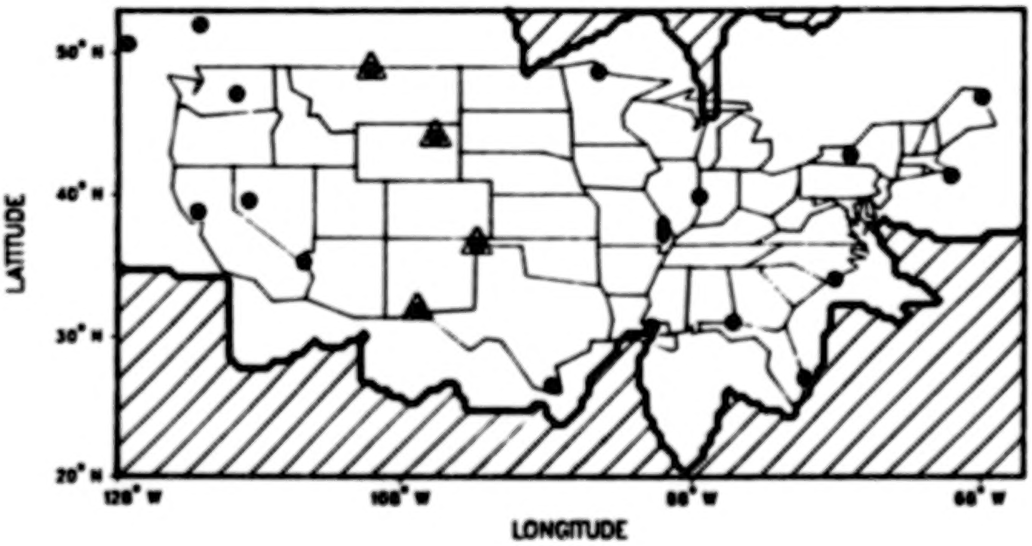
50° N
40° N
30° N
20° N
120° W
100° W
80° W
60° W
LATITUDE
LONGITUDE

Figure 2. Predicted LORAN-C pseudorange coverage. Coverage is computed under the following assumptions:

- "Mid-continent gap" is filled
- All-in-view solution using 4 or more stations
- SNR greater than -10 dB
- HDOP (horizontal dilution of precision) less than a factor of 7.8
- Receiver bandwidth = 20 kHz
- Atmospheric noise values used are for the summer season, based on C.C.I.R. Report No. 322
- Search increment = 0.5'

AIRCRAFT WEATHER DATA DISSEMINATION SYSTEM

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SUMMARY

There exists the need for an automated aircraft weather data dissemination system to provide real-time weather data to the airplane cockpit. The need has been recognized both by the airspace users and by the Federal Aviation Administration (FAA). Although the development of such a system is planned, the system requirements have not yet been adequately defined, and development of a prototype weather uplink system has not yet been accomplished.

Ohio University is currently conducting research in order to develop an optimal method of accomplishing the transmission of weather data for an automated aircraft weather data dissemination system. The present status of this research and future research plans are the subjects of this paper.

INTRODUCTION AND STATEMENT OF PROBLEM

For hazardous weather avoidance and for efficient utilization of available airspace, the pilot has a critical need for weather information which is both accurate and timely. The transmission of these data to the pilot must make efficient use of an already overcrowded frequency spectrum. Additionally, this information must be easily obtainable by the pilot and must be presented in a way to best allow pilot interpretation.

The aircraft pilot must constantly be aware of weather conditions both in the immediate vicinity and in the planned flight path of the aircraft. These weather conditions affect both the safety and the efficiency of the flight. Safety is compromised if the aircraft is operated in areas of hazardous weather conditions such as severe thunderstorm cells and turbulence. Even in less hazardous weather areas, decreased aircraft efficiency can result due to winds aloft. Also, a lack of knowledge of exact areas of hazardous weather may force the pilot to choose inefficient routes around these areas.

Currently, weather information is provided to the pilot through a system which was developed to serve the aviation needs of many years ago. Aircraft at that time were fewer in number and were also slower. In addition, less sophisticated weather data gathering and forecasting capabilities greatly limited the amount of useful weather data available to the pilot.

The current aviation weather system relies upon several ground-based focal points to direct and process weather data as gathered from various sources. The pilot receives the information by voice communication with ground-based controllers. As a result, the system is subject to significant time delays and inaccuracies in reported weather data. Also, due to the workload of the controllers and the congestion of the radio communication channels, the pilot must often expend too much effort to obtain these data.

The federal airways are becoming increasingly crowded, and the controllers are facing greater workloads. Additionally, larger amounts of weather data are becoming available. With weather playing a significant role in many aircraft fatalities, it is important to develop an improved aviation weather data dissemination system.

PROBLEM SOLUTION

Fortunately, the importance of obtaining accurate weather data is recognized, and significant improvements have been made. Since World War Two, capabilities for the gathering of weather data and for weather forecasting have improved dramatically. Modern technology in radar systems and in satellite imaging have played a large role in this improvement. Future improvements will occur through continued technological advances and through better integration of the systems.

The Federal Aviation Administration (FAA) has established a number of commitments for modernization of the current aviation weather system (refs. 1 and 2). Included in these plans are more sophisticated remote weather sensing capabilities (including Next-Generation Weather Radar NEXRAD), automated weather data gathering facilities, and direct pilot access to ground-based weather data. Through the implementation of these programs, significant improvements to the overall weather data dissemination system will be realized.

Highly important to the modernized aviation weather system plan is the development of an aircraft weather data dissemination capability. Such a capability will provide the pilot direct access to ground-based weather data and will replace the current practice of voice communication of weather data to the pilot. This capability will by itself be responsible for alleviating many of the problems with the current overall aviation weather system.

An aircaft uplink capability is desired by airspace user organizations (ref. 2), and although the capability is included in future plans, an immediate need exists for such a system. The current FAA future plans rely upon the Mode S data link to accomplish aircraft weather data dissemination (refs. 1 and 2). Use of Mode S will result in significant implementation delays, and the system might not be capable of meeting all of the requirements described in this paper. For these reasons, it is important to consider all possible transmission modes for the aircraft weather data dissemination system.

REQUIREMENTS

The requirements for an aircraft weather data dissemination system must be defined before such a system can be developed. The requirements described here are derived from documented research in this area, and from other sources referenced by this paper (refs. 3 through 8).

1. The pilot has an obvious need for current information about weather conditions which could compromise the safety of the flight. Critical conditions such as severe thunderstorms, windshear, icing, and turbulence should receive top priority for dissemination to the aircraft.	HAZARDOUS WEATHER CONDITIONS
2. Current National Weather Service WSR 57/74 radars provide more accurate reflectivity patterns over a greater area than either airborne or surveillance radar. Although the current aviation weather network has access to these radar products, the reflectivity patterns must be manually interpreted and described to the pilot by voice transmission. Also, the data are outdated by the time they pass through the network and to the pilot. When operational, the Next-Generation Weather Radar (NEXRAD) system will provide even more detailed weather information including location of windshear. In order for this information to be effectively utilized, it must be available to the pilot in real time.	REFLECTIVITY PATTERNS (WSR 57/74 AND NEXRAD PRODUCTS)
3. The pilot has a need for hourly sequences of surface conditions such as provided by a surface analysis (SA). Sequences permit the pilot to observe trends that might affect the aircraft landing. The availability of automated altimeter settings would eliminate the need for manual voice transmission of these data.	SA's
4. Terminal Forecasts (FT's) and Area Forecasts (FA's) consisting of both text and graphics data would enhance flight planning.	FA's AND FT's
5. Weather information which is critical to the safety and efficiency of the flight but does not represent an immediate threat should also be provided for the planned flight area. This information would aid in flight planning. Critical weather would include turbulence, ice, thunderstorms, and low visibility areas.	CRITICAL WEATHER MAPS
6. Information such as Pilot Reports (PIREPS), Significant Meteorological Information	TEXT INFORMATION

(SIGMETS), Airman's Meteorological Information (AIRMETS), and Notices to Airmen (NOTAMS) could be transmitted digitally through the aircraft weather data dissemination system. This would be much more efficient than the current dissemination by voice or hard copy.

(PIREPS, SIGMETS, AIRMETS, NOTAMS)

7. As the amount of digital data necessary to represent images decreases, the transmission of weather images obtained by satellite will become more practical. Such images would be of value to the pilot for route planning.

   SATELLITE IMAGES

TRANSMISSION REQUIREMENTS

1. In order to provide a maximum amount of weather data in near-real time, the uplink update rate must be maximized. This can be accomplished by minimizing the time required to process and transmit the data.

   MAXIMUM UPDATE RATE

2. The system must provide adequate spatial coverage to allow data uplink at any flight altitude. Also, transmission to aircraft on the ground is important when airport delays necessitate updated pilot weather briefings before takeoff.

   ADEQUATE SPATIAL COVERAGE

3. Due to high pilot workloads, the required effort to obtain weather data should be minimized.

   MINIMUM PILOT EFFORT

4. The frequency spectrum is already overcrowded, and future systems will tax this resource even further. The transmission of the weather data should maximize spectrum conservation.

   SPECTRUM EFFICIENCY

RESEARCH OBJECTIVE

There exist many ways to implement the aircraft weather data dissemination capability. All methods possess inherent strengths and weaknesses. Research is under way at Ohio University's Avionics Engineering Center to develop an optimal method of accomplishing this transmission.

RESEARCH TO DATE

Ohio University has developed a testbed capability for the development of an aircraft weather data dissemination system. The system is operational and has been used for the transmission of radar reflectivity data to an aircraft. Shown in figure 1, the system accesses National Weather Service (NWS) radar sites by telephone line. The data are supplied to a Very High Frequency (VHF) communication transmitter where they are transmitted to the aircraft. At the aircraft, these data are received, demodulated, and supplied to a dedicated processing system. This system converts the radar data to raster scan format for output on a standard Cathode Ray Tube (CRT) display.

FUTURE RESEARCH

Shown in figure 2 is the system under development at Ohio University. Data compression is utilized to minimize transmitted data, and the data are transmitted over a spectrum-efficient data link. The system will meet the requirements outlined earlier and should provide an optimal means for the transmission of weather data to the cockpit. The system will be developed utilizing the existing uplink capability for testing and will be flight-tested for final evaluation. Current research is under way to determine a maximally efficient data compression method for cloud and radar reflectivity boundaries, as well as to develop an uplink transmission technique.

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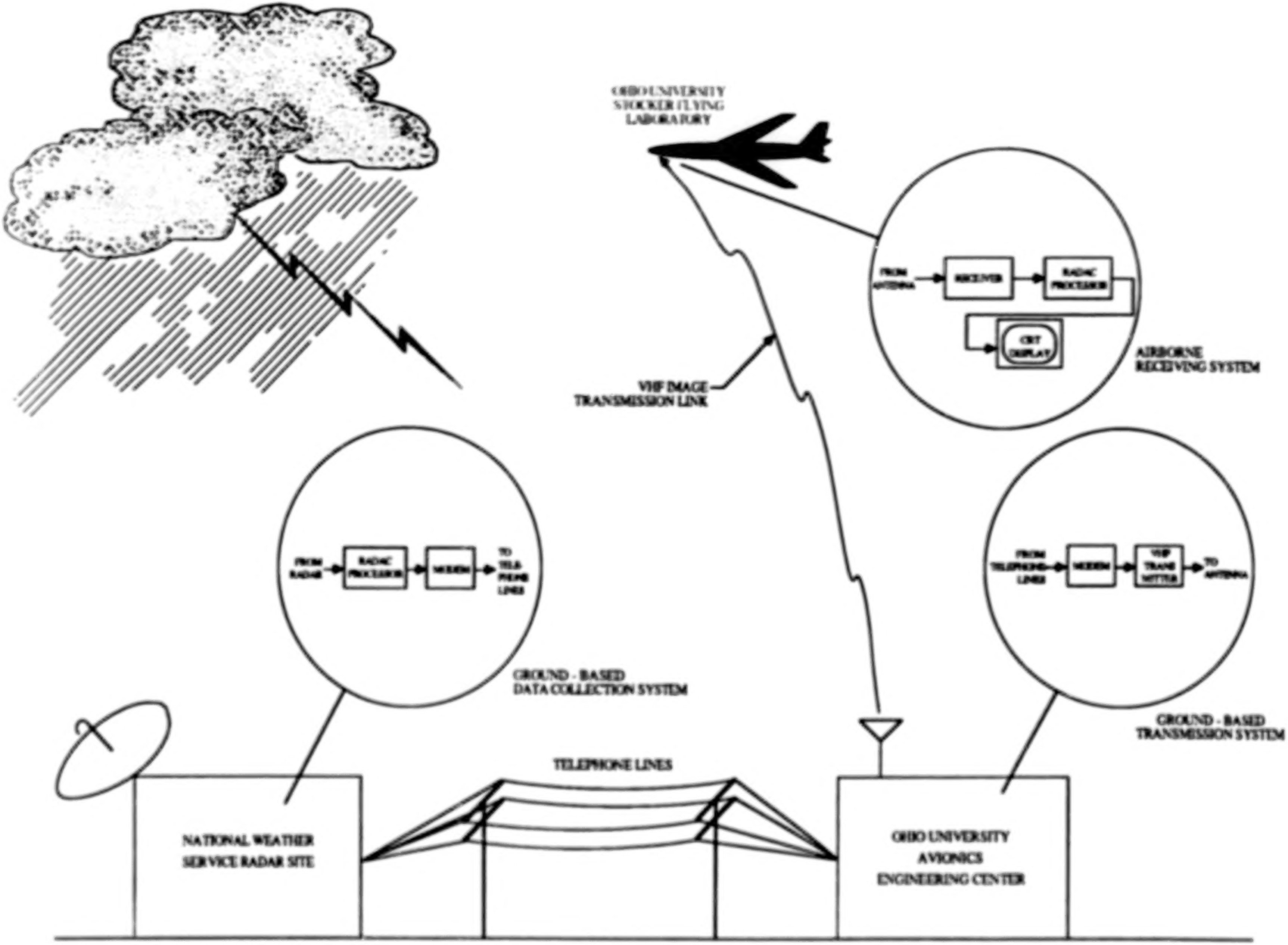
OHIO UNIVERSITY
STOCKER FLYING
LABORATORY
FROM
ANTENNA
RECEIVER
RADAC
PROCESSOR
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VHF IMAGE
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PROCESSOR
MODEM
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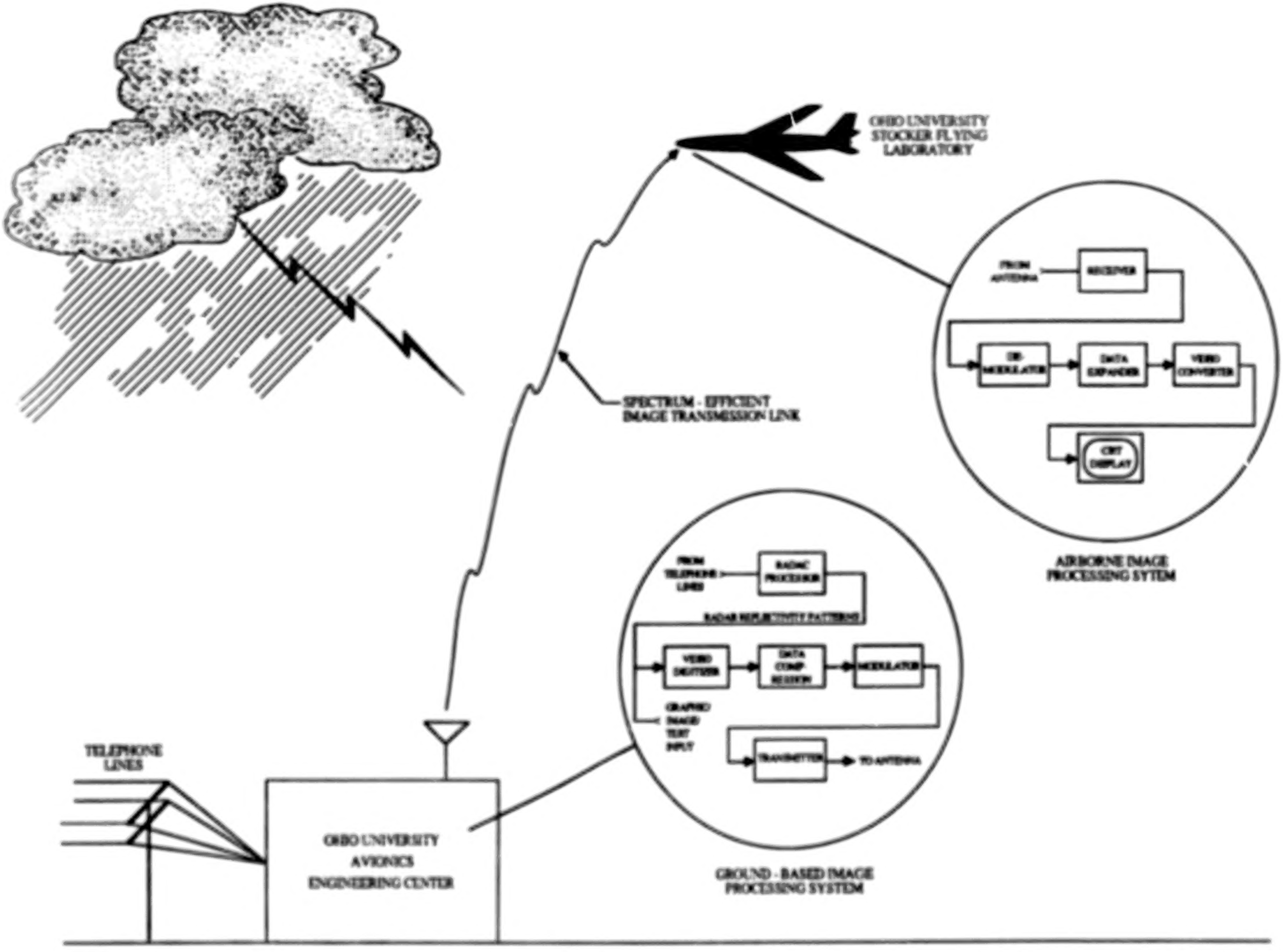
LINES
GROUND - BASED
DATA COLLECTION SYSTEM
FROM
TELEPHONE
LINES
MODEM
VHF
TRANS-
MITTER
TO
ANTENNA
GROUND - BASED
TRANSMISSION SYSTEM
TELEPHONE LINES
NATIONAL WEATHER
SERVICE RADAR SITE
OHIO UNIVERSITY
AVIONICS
ENGINEERING CENTER

Figure 1. Aircraft weather data dissemination system in operation.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DATA COMP-RESSION
MODULATOR
GRAPHIC IMAGE TEXT INPUT
TRANSMITTER
TO ANTENNA
GROUND - BASED IMAGE
PROCESSING SYSTEM
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Figure 2. Aircraft weather data dissemination system under development.

PRINCETON UNIVERSITY

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INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1987

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SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University, a program emphasizing graduate and undergraduate student research, proceeded along three avenues during the past year:

- Guidance and Control Strategies for Penetration of Microbursts and Wind Shear
- Application of Artificial Intelligence in Flight Control Systems
- Reinvention of the General Aviation Airplane

It has become apparent that severe downdrafts and resulting high velocity outflows caused by microbursts present a significant hazard to aircraft on takeoff and final approach. Microbursts, which are often associated with thunderstorm activity, also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are known and applied.

While a number of simulation studies have been directed at the problem, there are varied opinions in the flying community regarding the best piloting procedures, and optimal control strategies have only recently been defined. Graduate student Mark Psiaki completed a study of optimal trajectories for penetration of microbursts when encounter is unavoidable. His initial work (reported earlier) showed that simple control laws could greatly reduce an aircraft's response to wind shear. His Ph.D. thesis [1] presents flight envelopes within which optimal application of throttle and pitch control produce acceptable deviations from nominal takeoff and landing flight paths for a jet transport and a propeller-driven general aviation aircraft. Although the response mechanism is the same, jet transport and general aviation aircraft behave somewhat differently in microbursts; the larger, heavier aircraft are more adversely affected by variations in the horizontal wind, while the smaller, lighter aircraft have greater difficulty with the downdraft.

Attention is now being directed at optimal closed-loop control laws for wind shear encounter that could be executed in "real time." Graduate student Amit Joshi is developing a real-time fixed-based cockpit simulation as an element of this research, with assistance from undergraduates Lucille Springen [2] and Jeffrey Seinwill [3].

Undetected system failures and/or inadequately defined recovery procedures have contributed to numerous air carrier incidents and accidents. The infamous DC-10 accident at Chicago's O'Hare Airport, in which loss of an engine pod, subsequent loss of subsystems, and asymmetric wing stall led to disaster, provides a prototype for the kind of tragedy that could be averted by intelligent flight control systems. (An intelligent control system is one that uses artificial intelligence concepts, e.g., an expert systems program, to improve performance and fault tolerance.) Although many methods of modern control theory are applicable, the scope of the problem is such that none of the existing theories provides a complete and practical solution to the problem. At the same time, heuristic logic may be applicable, but it has yet to be stated in satisfactory format.

Graduate student David Handelman is developing a knowledge-based reconfigurable flight control system that will be implemented with the Pascal programming language using parallel microprocessors. This expert system could be considered a prototype for a fault-tolerant control system that could be constructed using existing hardware. The knowledge-based flight control system is specified initially and tested using the LISP programming language. When desired logic is determined, the corresponding Pascal code is generated automatically. Details of knowledge base development, expert system logic, and initial evaluations are contained in Ref. 4.

In a parallel effort, graduate student Chien Huang is using LISP to investigate the utility of a string-oriented, recursive logical system in the same role. A principal distinction between this and the previous approach is that flight control code will be modified in response to control system failures. During the year, Mr. Huang developed a heuristic approach to failure model determination [5], and he studied the application of implicit model following to the determination of control system gains following component failures [6]. As a consequence of this work, he and fellow graduate student Stephen Lane developed a heuristic algorithm for solving the so-called "Traveling Salesman Problem" [7].

Helping a pilot make quick decisions under high work load conditions is important for aircraft missions of all types. In research principally supported by an Army Research Office contract, graduate student Brenda Belkin is developing an expert system of expert systems called AUTOCREW [8]. The component systems are identified with hypothetical crew members (e.g., copilot, navigator, and so on), facilitating the assignment of tasks, rules, and data within parallel knowledge bases. AUTOCREW performs a cyclical search in which the director expert system, the electronic analog of the aircraft commander, establishes goals that invoke the crew-member expert systems. The crew members then perform tasks such as observation, monitoring, and control in response to continuing needs as well as special requests from the director. The application of AUTOCREW to civil jet transports is apparent, and Ms. Belkin has participated in the Air Transportation Technology Program with this in mind.

For all practical purposes, the production of small general aviation (GA) airplanes in the U.S. has come to an end. Fewer than a thousand four-seaters were produced in 1986, and the principal GA manufacturers have all but abandoned the business. Although there are many reasons for the erosion of this industry, outmoded technology is the most important. General aviation has a potentially significant role to play not only in the National Transportation System but in the economic infrastructure of the country. Revival demands reinvention of the small plane, in what might be called a Modern-Equipment General Aviation airplane. Causes of the problem and possible solutions are presented in Refs. 9 and 10. There is a wealth of fundamental research to be done in this area, much of it already underway in the Air Transportation Technology Program. Seniors Joakim Karlsson and Florence Gramignano have begun independent work projects related to the design and control of such aircraft [11,12].

ANNOTATED BIBLIOGRAPHY OF 1987 PUBLICATIONS

1. Psiaki, M., "Control of Flight Through Microburst Wind Shear Using Deterministic Trajectory Optimization," Princeton University, Department of Mechanical and Aerospace Engineering Report No. MAE-1787-T, Ph.D. Thesis, Oct 1987.

Aircraft control strategies that minimize the hazard of longitudinal flight through microburst wind shear are developed and analyzed, principally using deterministic trajectory optimization and, to a lesser extent, classical control theory. The purpose is to determine the ultimate limits to safe performance in a microburst and to develop control strategies that achieve such performance. Over 1,100 optimal trajectories were computed for jet transport and general aviation aircraft flying through idealized and actual microburst profiles. They were generated using a new successive-quadratic-programs optimization algorithm that handles inequality constraints directly. The safe-performance limits show that both aircraft types can penetrate very severe downbursts if controlled properly; nevertheless, even the best control strategies have their limits, and purposeful flight through severe disturbances should be avoided.

2. Springen, A. L., "Twin-Jet Transport Simulation," Princeton University Senior Independent Work Project Final Report, May 1987.

A data base of aerodynamic, inertial, and thrust characteristics of a typical twin-jet transport configuration was assembled. The transport mathematical model will be used in cockpit simulations to be conducted with a fixed-base simulator in Princeton's Laboratory for Control and Automation. The simulator uses a special-purpose parallel computer controlled by an IBM PC-AT computer to solve trajectory and control equations, a Silicon Graphics IRIS workstation to display the visual scene, and a single-person crew station for interface with the pilot.

3. Seinwill, J., "Design and Testing of Cockpit Displays for a Flight Simulator," Princeton University Senior Independent Work Project Progress Report, Jan 1988.

A real-time simulator has been designed to investigate various flight phenomena. Currently, the simulator has not been equipped with a full complement of cockpit instruments. During the fall semester, development of an artificial horizon was initiated, and essential elements of the display were completed.

4. Handelman, D., and Stengel, R., "An Architecture for Real-Time Rule-Based Control," Proceedings of the 1987 American Control Conference, Minneapolis, June 1987, pp. 1636-1642.

A method for control employing rule-based search is reviewed, and a Rule-Based Controller achieving economical real-time performance is described. Code optimization, in the form of LISP-to-Pascal knowledge base translation, provides real-time search execution speed and a processing environment enabling highly integrated symbolic and numeric computation. With a multiprocessor software architecture specifying rule-based protocol for control task implementation within a multi-microprocessor system, the controller realizes a set of cooperating real-time expert systems. Based on experience gained through the design and implementation of a Rule-Based Flight Control System, the proposed approach appears applicable to a large class of complex control problems.

5. Huang, C., and Stengel,R., "Failure Model Determination in a Knowledge-Based Control System," Proceedings of the 1987 American Control Conference, Minneapolis, June 1987, pp. 1643-1648.

A technique for determining the most probable failure state of a restructurable control system is presented. The approach is to build a knowledge base that contains and makes use of inference mechanisms to deduce the most likely failures given the symptoms. The analysis is first carried out in a local sense, where only probabilistic information and causality are used to generate failure models, then in a global sense, where the models are grouped and heuristics are used to prune the number of candidate models. Procedures are illustrated using failure patterns of a generic data base as well as a fault scenario for a hypothetical helicopter flight control system. It is concluded that the methods are potentially capable of handling generic failures and thus are useful in truly restructurable control systems.

6. Huang, C., and Stengel, R., "Restructurable Control Using Proportional-Integral Implicit Model Following," Proceedings of the 1987 AIAA Guidance, Navigation, and Control Conference, Monterey, Aug 1987, pp. 277-286.

Studies of a proportional-integral implicit model-following control law are presented. The research focuses on the ability of the control law to recover the performance of a failed system to its pre-failure level. Properties of the implicit model-following strategy are examined, and conditions for control reconfiguration are stated. The control law is applied to the lateral-directional model of an aircraft, and control restructuring is shown for changes in control and system matrices. It is concluded that the implicit model-following scheme is a good candidate for control reconfiguration.

7. Huang, C., and Lane, S., "A Heuristic Approach to the Traveling Salesman Problem," Proceedings of the 1987 AIAA Guidance, Navigation, and Control Conference, AIAA Paper No. 87-2338, Monterey, Aug 1987, pp. 459-464.

An approach for solving the traveling salesman problem as formulated in the AIAA Artificial Intelligence Design Challenge is presented. The approach is based on heuristic measures involving intercity fares, city values, and value-to-fare ratios. Other heuristic factors take into account the available budget, the expected trip cost, and the likelihood of low-cost hub cities. Monte Carlo simulations show that this heuristic method produces optimal solutions over 90 percent of the time for problems dominated by fare, and at least 55 percent of the time for problems dominated by value-to-fare ratio. The average measure of optimality for the heuristic solutions exceeds 0.95 in both cases.

8. Belkin, B., and Stengel, R., "Cooperating Rule-Based Systems for Aircraft Navigation and Control," Proceedings of the 26th IEEE Conference on Decision and Control, Los Angeles, Dec 1987, pp. 1934-1940.

This paper examines the application of artificial intelligence theory in the flight domain of a military aircraft. Nine rule-based systems were implemented to demonstrate complex system cooperation in combat aircraft operations. The organization of tasks within each rule-based system is described, and details of knowledge-base development and implementation are given. An interactive simulation test-bed was developed to provide a realistic simulation of intersystem cooperation of parallel rule-based systems. Software tools developed to aid in fast prototyping of rule-based systems are described. Search effort metrics were used to quantify and compare light and heavy work load phases of a combat mission. Methods developed have direct application to civil air transport systems.

9. Stengel, R., "Time to Reinvent the General Aviation Aircraft," Aerospace America, Vol. 25, No., 8, Aug 1987, pp. 24-27.

Current designs for general aviation airplanes have become obsolete, and avenues for redesign must be reconsidered. New designs should incorporate recent advances in electronics, aerodynamics, structures, materials, and propulsion. Future airplanes should be optimized to operate satisfactorily in a positive air traffic control environment, to afford safety and comfort for point-to-point transportation that is at least comparable to automobile travel, and to take advantage of automated manufacturing techniques and high production rates. These requirements have broad implications for airplane design and flying qualities, leading to a concept for a Modern Equipment General Aviation (MEGA) airplane. Synergistic improvements in design, production, and operation can provide a much needed fresh start for the general aviation industry and the traveling public. Achieving these goals requires nothing less the reinvention of the small airplane, providing new opportunities and requirements for research.

10. Stengel, R., "Planning for General Aviation in the 21st Century," presentation to the NASA Aeronautical Advisory Committee Ad Hoc Committee on General Aviation, NASA Langley Research Center, Sept 1987.

Consideration is given to factors affecting the supply and demand of general aviation airplanes. It is noted that recent gross expenditures for general aviation airplanes tend to be independent of the number of units sold, leading to a traditionally shaped demand curve (unit price vs. number sold). Nevertheless, the public is less willing to spend as much for small airplanes as it spent a decade ago, indicating a perceived loss in utility. The supply curve (unit price vs. number sold) is flat or decreasing with increased number of units sold, and the rate of decrease is heightened by the incorporation of advanced technology in production. This gives rise to the possibility of two market points: a high-price, low-volume point and a low-price, high-volume point. Resurgence of the general aviation industry requires concerted efforts to restore perceived utility of this transportation mode and to achieve the latter market point.

11. Karlsson, J., "Preliminary Design for a Modern Equipment General Aviation (M.E.G.A.) Aircraft," Princeton University Senior Independent Work Project Progress Report, Jan 1988.

A single-engine/propeller aircraft design is proposed to revitalize the U.S. general aviation industry. The objective of the design is to improve safety over existing designs, improve cost efficiency, and to provide easy-to-fly aircraft, while maintaining good performance qualities. The design approach is defined, followed by the resulting design procedure, and a preliminary design is presented. Social, economic, and political issues are discussed briefly, and preliminary performance characteristics are discussed.

12. Gramignano, F., "Preliminary Consideration of Redundant Controls for General Aviation Aircraft Using Princeton's Navion as a Baseline," Princeton University Senior Independent Work Project Progress Report, Jan 1988.

The subject of this work is the introduction of redundant controls, automatically selected by a control blender in case of a control failure, for general aviation airplanes. A quantitative assessment of a three-surface configuration was made, using the Navion aircraft as a starting point. Redundant controls were modeled by decoupling existing control surfaces and adding a hypothetical canard surface with moving trailing-edge flaps. A simple linear blender would be used to command the controls following actuator failure. Preliminary analysis indicates that concern must be addressed to the problems of control saturation following such failures.

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IT'S TIME TO REINVENT GENERAL-AVIATION AIR TRAFFIC CONTROL

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Princeton University

INTRODUCTION

A steady decline in the general aviation industry has come about for many reasons, including a skyrocketing rate of legal claims against manufacturers, use of outmoded technologies in design and production, and dramatic increases in the sticker price of new aircraft. Current and planned changes in the National Airspace System may be equally significant in discouraging general aviation if specific steps are not taken to assure ready access to the airways for small planes. Given the opportunity, general aviation could become a significant, beneficial factor in the National Transportation System, complementing the use of automobiles on one end and commercial transport aircraft on the other for a wide range of inter-city trips. However, this opportunity will not arise unless the air traffic control (ATC) system accounts for the natural differences between large and small aircraft. These differences are reviewed, and concepts for a Modern Equipment General Aviation-Traffic Control (MEGA-TC) System are presented.

General Aviation Is Being Designed Out of the National Airspace System

General Aviation Would Become an Important Element of the National Transportation System with Advanced Air Traffic Control

MEGA-TC

Goals and Assumptions
Elements of the Modern Equipment General Aviation-Traffic Control System

GENERAL AVIATION IS BEING DESIGNED OUT of the NATIONAL AIRSPACE SYSTEM

The National AirSpace (NAS) Plan currently being implemented by the Federal Aviation Administration (FAA) focuses principally on the needs of commercial aviation, which accounts for the overwhelming majority of air freight and passenger transportation in this country. While this focus is appropriate, it need not preclude the development of complementary plans for general aviation.

For the most part, the airspace needs of large and small aircraft are quite different, coming into conflict only in the vicinity of major airports and at adjacent navigation waypoints. Whereas the principal enroute ATC objective for commercial transports is to maintain maximum flow within a few, well-defined corridors, a comparable objective for general aviation is to enhance the safety and operational efficiency of a more free-form pattern of route planning and scheduling. Metering and spacing should be less of a factor for small aircraft, while improved collision avoidance/proximity warning and traffic/weather uplink should be given greater emphasis.

The capability for flight under a wide range of weather and traffic conditions is, in principle, available for general aviation now, but the cost of airborne equipment is high, and a high level of pilot proficiency is required. Even then, the excessive work load associated with single-pilot instrument flight prevents all but the most capable pilots from using their aircraft to the fullest.

- Current NAS Planning is Effectively Neglecting GA, at Best
  - Lack of Collision Avoidance/Proximity Warning and Traffic/Weather Uplink for Small Aircraft
  - Focus on Hub Airports and Jetway Flow Control
- Current ATC Forces GA Aircraft to Compete with Commercial Aircraft (CA) for Air and Runway Space
  - Current ATC Creates Bottlenecks at Airports and Navigation Waypoints
  - Priority (Rightfully) Given to Larger Aircraft
- Current IFR Systems Create Excessive Single-Pilot Workload
  - [illegible] Proficiency and Currency
  - Reluctance to Give GA Pilot "Too Much Information"
- Cost of IFR Modernization for GA Has Been High

"WIN-WIN" SOLUTIONS TO CA/GA AIR TRAFFIC CONTROL PROBLEMS CAN BE FOUND

ATC improvements tailored to the needs of small airplanes need not deter or conflict with improvements directed toward commercial users. Large and small aircraft occupy different airspace while enroute, and terminal-area conflicts can be minimized by encouraging small aircraft to make point-to-point flights rather than hub-to-hub flights. In most instances, personal trips begin and end at locations away from hub airports and city centers; it should be possible to address these needs for personal travel by enhancing the capabilities of small airports that serve local suburban and rural areas. Providing simple, low-cost, all-weather ATC services at small airports (as well as improved interfaces to the ground transportation infrastructure) would make it possible for small planes to avoid hub airports. Resulting increased use of general aviation would off-load the commercial air system, slowing the inexorable demand for NAS services by commercial users.

There are two central requirements for enhanced general aviation ATC: positive control of all GA aircraft in most areas of the country and a new physical model to describe control objectives. Comprehensive positive control that is applied in visual as well as instrument meteorological conditions can be beneficial to both the users and the controlling agencies if care is exercised in making the system as non-intrusive as possible. The burgeoning field of electronics will, for example, make it possible for a departing aircraft to make its intent known to controllers as the pilot is performing preflight checks. Approved routing and scheduling that is consistent with the performance and instrumentation characteristics of the aircraft can be transmitted from the ATC center to the aircraft before it is airborne. Hardware and software design should use the paradigm of molecular diffusion rather than fluid flow, as detailed in succeeding figures.

GA-ATC Improvements Need Not
Deter CA-ATC Improvements

Flight Profiles and Ground Tracks of
CA and Small GA (SGA) Aircraft Have
Little Reason to Conflict

Terminal Area/Runway Conflicts
Can Be Reduced By Addressing
Proper Goals for GA Travel, i.e.,
Point-to-Point, Not Hub-to-Hub,
Transportation

Increased GA Use Off-Loads CA

Positive Control Will Aid GA
in the Future

Flow Control for CA,
Diffusion Control for GA

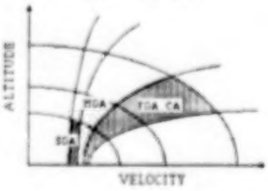
GA-ATC Improvements Can Be
Compatible with the NAS Plan

DISTINCTION BETWEEN AIRCRAFT CLASSES

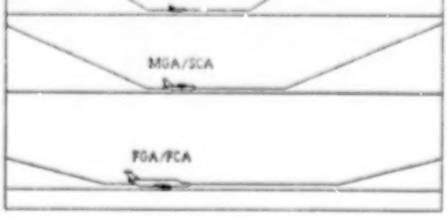
The flight envelopes of airplanes are dominated by their aerodynamic, inertial, and thrust characteristics. One important characterization of an aircraft's flight envelope is the altitude-velocity space delimited by maximum and minimum dynamic pressure (parabolic variations in altitude with airspeed) and maximum ceiling (shown here as elliptical segments of constant total energy). All aircraft whose principal mission is transportation over significant distances tend to operate near the intersection of the ceiling and the speed limit, which varies somewhat as the aircraft lightens with fuel burn. Small general aviation (SGA) aircraft, such as those with single reciprocating engines or helicopters, have low wing loading (weight divided by wing area) and low power; therefore, SGA planes spend most of their time in a narrow region. The speed and altitude of medium-size GA (MGA) planes like multi-engine turboprop configurations are greater and tend not to overlap with the other classes, except during takeoff and landing. Fast GA (FGA) and commercial airplanes (CA) powered by turbofan or advanced propfan engines compete for the same flight envelope.

Space allotted to the takeoff and landing of these aircraft types can be similarly partitioned. The SGA airplane can use short runways and achieve steep climb out and descent paths; FGA/CA aircraft require long runways and may use shallower departure and arrival paths. It is clear that the three aircraft types can use entirely different airspace segments and terminal-area facilities on the basis of dynamic characteristics alone. A wisely framed NAS plan will take advantage of these differences to minimize conflicts between differing aircraft types while retaining the transportation benefits for which the system is intended.

Flight Envelopes



Landing and Takeoff Profiles

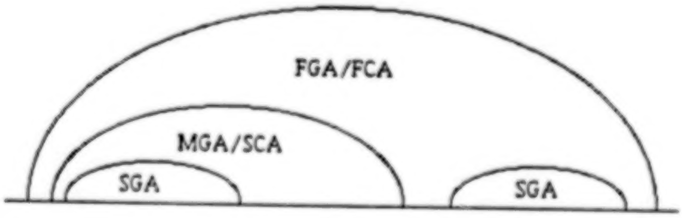


AIRSPACE and GROUND TRACKS

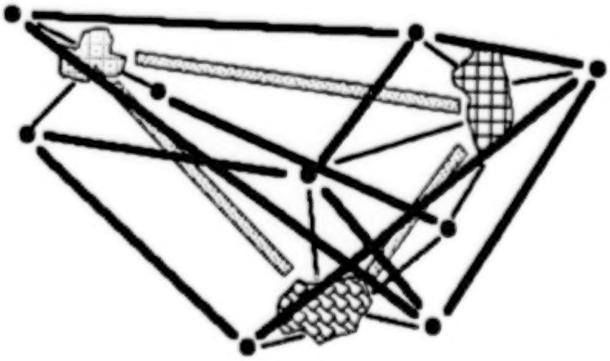
As introduced on the previous slide, the three principal aircraft types typically compete for airspace only at the beginning and end of their flights. SGA aircraft are well-suited for point-to-point travel needs, while CA aircraft provide a faster, more economical and efficient solution for hub-to-hub travel. It is best for air transportation if conflicts between commercial and private aircraft can be minimized by encouraging a natural partitioning of the airspace. Providing simple, low-cost, all-weather ATC services that can be accessed from any small airport (including private grass strips) would promote their use by small planes. This implies that an ATC system that fosters general aviation should require a minimum of dedicated ground equipment at each airfield. Good interfaces with the ground transportation infrastructure also must be available as well, although this is not an ATC issue.

Because a limited amount of GA traffic into hub airports is desirable -- particularly for commuter airlines and air taxis -- hub airports should be furnished with one or more stub runways dedicated to small planes. Small planes should be prohibited from using CA runways at hub airports except under emergency conditions. This again is not strictly an ATC issue; however, it is so important to the efficient operation of the commercial air system that it should become an element of national policy.

Mission Profile Umbrellas



Point-to-Point, Hub-and-Spoke, and Hub-to-Hub Ground Tracks

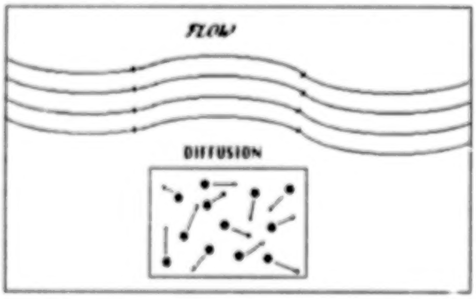


AIR TRAFFIC CONTROL for POINT-to-POINT TRAVEL

Modeling air traffic as a fluid flow is natural if all aircraft tend to fly between the same points and at the same airspeeds. This model can be modified to account for aircraft flying at different speeds and in opposite directions by considering "laminar" flow in adjacent channels -- in the NAS case, at different flight levels and with horizontal offsets. If, however, aircraft tend to depart from and arrive at locations that are more or less randomly distributed, the laminar flow analogy is not a useful one. A better model could be based on the motions of molecules in a gas, or molecular diffusion. Even though the path of a single molecule is deterministic, the overall pattern appears random as natural forces deflect the motions of adjacent molecules.

In framing a diffusion-based ATC model, it is clear that some mechanism for preventing airplanes (the "molecules") from bumping into each other is of critical importance. If there are many such airplanes (which is the desired goal) and if safe flight is paramount (which it is), then fail-safe collision avoidance is an essential attribute of the ATC system. Fail-safe performance is most readily obtained by providing dissimilar redundancy in an already reliable system. In the current context, this means that both ground and airborne surveillance of local traffic are required. Each aircraft must have a dependable means of detecting and avoiding threat aircraft based on its own observations as well as ground-based traffic advisories. Conflict situations can be minimized by direct routing of aircraft, that is, by reducing the need for aircraft to occupy common airspace during transit.

Flow Control vs. Diffusion Control



Requirements for Diffusion-Based
Air Traffic Control

Fail-Safe Collision Avoidance

Positive Knowledge of Aircraft Position and Velocity
on Ground and In Aircraft

Fail-Safe IFR Capability/Autonomous Navigation

Cooperative Monitoring to Avert Blunders

Direct Routing to Avoid Hubs, Established Air Routes,
and Overflight of Navigation Aids

GOALS and CHARACTERISTICS of MEGA-TC

Concepts for a Modern Equipment General Aviation-Traffic Control (MEGA-TC) System can be based on the philosophy presented above. All active aircraft should be subject to positive control, navigation, and surveillance in all weather conditions. They should be equipped with self-contained collision-avoidance systems that are compatible with all other airborne aircraft; this may call for a standardized cooperative system. All aircraft should be equipped with Mode-C transponders for ground surveillance; the transponder also could function with airborne threat-alert/collision-avoidance (TCAS) systems. Data uplink as well as downlink is required for all aircraft; in the near term, this could be based on Mode-S electronics; however, bandwidths would be low, and data channels would be easily saturated in heavy traffic. A better long-term solution is the use of a Time-Division-Multiple-Access (TDMA) link, as illustrated in the next chart.

Incorporating artificial intelligence (AI) concepts in computer programs for database management, surveillance, and control is a key strategy for the development of a high-performance air traffic control system. One important consequence is that automated clearance and flight planning can be provided efficiently and with easily understood interfaces for pilots and controllers.

There will be a requirement for massive data transfer in the future ATC system, using both broadcast and dedicated channels. Some services will be handled best by local-area networks, and it is reasonable to assume that discretionary services, such as in-flight weather advisories, optimization advisories, and non-flight-critical communication, can be provided by commercial vendors.

Positive Control, Navigation, and
Surveillance for All Aircraft

Collision Avoidance Systems and
Mode-C Transponders forAll Aircraft

Mode-S Data Link Near-Term,
Time-Division-Multiple-Access Link
Long-Term

Automated Clearance and
Flight Planning, with Minimal Delays

Major Use of AI Technology

In-Flight Commercial
Data Base Services
Weather Advisory
Route/Profile Optimization
Communication

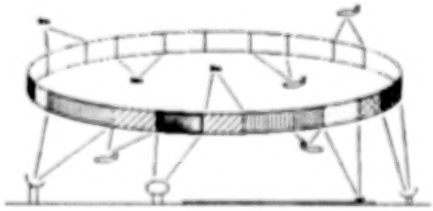
TDMA COMMAND, NAVIGATION, and SURVEILLANCE

Time-Division-Multiple-Access (TDMA) links are local-area radio networks operating on dedicated transmission frequencies that have many similarities to computer networks. Transmission protocols for TDMA links can be structured in much the same way, with user application, transport, internet, and physical layers, as introduced in the accompanying presentation by Amit Joshi. Some of the current computer network protocols originated in the field of short-wave amateur radio communication; hence, the association is direct.

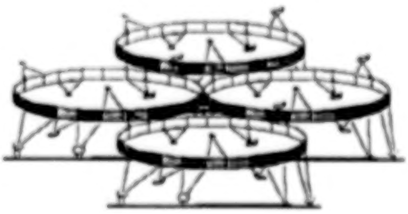
TDMA links for command, surveillance, and navigation would operate at line-of-sight frequencies and would be maintained by close coordination of participating units, including aircraft, ATC centers, weather stations, airports, and commercial vendors in local areas. These areas would be defined geographically and would be sized to minimize the link switching and monitoring requirements of aircraft operating at typical GA airspeeds. Airborne TDMA units would have a multi-frequency capability to allow interaction with an active link and monitoring of links serving areas which the aircraft might enter within the next few minutes. The airborne link would automatically switch from one link to the next as its flight progressed. The switching decision would be based on aircraft position, as every aircraft would know its true location with high precision.

Transmission powers would be kept relatively low to minimize interference between TDMA links in geographically separated regions. Channel bandwidths would be high as a consequence of the use of high carrier frequencies. Transmission protocols and waveforms should be chosen to minimize the possibility of inadvertent jamming by malfunctioning equipment or weather-related phenomena.

Basic TDMA Link



Interconnected TDMA Links



CONCLUSIONS

General aviation can be a prominent component of this country's transportation system, and, therefore, it can have a significant impact on the nation's economy. Because commercial and general aviation aircraft have substantially different flying characteristics, they tend to use different portions of the available airspace. An astute air traffic control policy will seek to leverage these fundamental differences, recognizing that conflict between the two is rarely unavoidable and that decentralization of at least some important functions (e.g., collision avoidance and dissemination of weather information) can improve both the safety and efficiency of the system. Encouraging each aircraft type to do what it does best is the key to the incorporation of today's and tomorrow's electronic and computational technology.

GA Has an Important Role to Play in the National Transportation System

CA and GA Compatibility Depends on Advanced Air Traffic Control

GA Should Receive Greater Attention in the NAS Plan

MEGA-TC Development is Consistent with Current Technology Advances

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The Modern Equipment General-Aviation Aircraft (M.E.G.A.)

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A single engine propeller aircraft design is proposed for an effort to revitalize the U.S. general aviation aircraft industry. The objective of the design is to improve safety over existing designs, improve cost efficiency and provide an easy-to-fly aircraft while maintaining good performance qualities. These objectives are realized through the use of modern, but proven, technology, as well as a high degree of system redundancy.

Introduction

In this report, we first identify the problems facing the U.S. general aviation aircraft industry, and then determine the causes behind these problems. It is seen that the slump of the sector is related to the use of outdated technology in the design and the production of the aircraft. With this in mind we define the initial specifications and then describe the design procedure used to obtain a preliminary design. Using this preliminary design, we carry out performance calculations to verify that the design meets the initial specifications.

- **Problem definition.**
- **Identification of causes (political and socio-economic analysis).**
- **Initial design specifications.**
- **Design procedure and results (technical analysis).**
- **Performance calculations.**

What are general aviation aircraft?

Before proceeding with the problem definition, we need to clarify what we mean by "general aviation aircraft". It is important to note that in this report we are concerned with single-engine propeller aircrafts only. However, the problems described apply to all categories of general aviation aircraft.

A general aviation aircraft is a small aircraft used for business, travel, or recreation. In this study we are only concerned with propeller-driven aircraft for 4-6 passengers. Examples from the "Big Three" include:

- **Cessna Skyhawk.**
- **Beechcraft Bonanza F33A.**
- **Piper (PA-28-181) Archer II.**

What is the problem?

The problem that we are addressing in this study is the current slump of the U.S. general aviation aircraft industry. Deliveries, sales, and exports have all declined drastically and rapidly over the last two decades. A once booming sector of the U.S. economy seems to be dying out.

The U.S. general aviation aircraft industry is dying. A once booming sector is deteriorating:

- **Deliveries are down from 10,000 in 1972 to 1,500 in 1987.**
- **Sales are down from $3 billion in 1981 to $1 billion in 1987.**
- **Exports are down from $800 million in 1981 to $260 million in 1987.**

What are the reasons?

The four main reasons behind the slump of the general aviation aircraft industry are the high costs or frequent unavailability of product liability insurance, the high production costs, the high certification costs, and the high operational risks involved. The high insurance rates are a result of the accident rate of general aviation aircraft, as are the certification costs. The low cost efficiency in production has been caused by increased material costs and outdated production processes. Since safety is partially a function of the technology used, it then follows that one of the underlying causes behind the decline of the industry is the use of outdated technology and production techniques.

The underlying cause is the use of outdated technology and production processes. This has manifested itself as follows:

- **Increased product liability insurance rates.**
- **Increased production costs.**
- **Increased certification costs.**
- **High operational risks.**

What will the M.E.G.A. change?

The purpose of the M.E.G.A. design is to solve the technology-related causes behind the current slump of the U.S. general aviation aircraft industry. It is believed that if modern but proven technology is used in the design and in the production process, the problems related to safety, high production and certification costs, and high product liability insurance rates can at least be partially solved. System redundancy, "good" in-flight handling characteristics, and some form of a flight programming expert system should yield additional improvements over existing designs.

The M.E.G.A. design will improve safety and reduce the costs of production:

- **System redundancy improves failure probability from $P=\zeta$ to $P=\zeta^2$.**
- **The design is stable and easy to fly.**
- **Improved safety through use of the Computer Assisted Flight Programming system.**
- **Use of proven off-the-shelf components and modern assembly techniques.**

Who are the policy makers?

In order to propose a solution for the problems described previously, it is first necessary to identify the relevant policy and decision makers. These can be subdivided into three broad categories: The public groups, the private groups, and other miscellaneous groups. The public groups involve those that are part of the U.S. government system, including the Congressional Aeronautical Advisory Committee (CAAC), the National Aeronautics and Space Administration (NASA), and the Federal Aviation Administration (FAA). Private groups include the General Aviation Manufacturers' Association (GAMA) as well as commercial airlines and aircraft manufacturers. Finally, the miscellaneous category consists of organizations such as the American Institute of Aeronautics and Astronautics (AIAA), and the Aircraft Owners' and Pilots' Association (AOPA).

There are three categories of policy and decision makers that have the power to influence the future of the general aviation industry:

- **Public groups: Senate and House committees (e.g. CAAC), NASA, FAA.**
- **Private groups: GAMA, commercial airlines and aircraft manufacturers.**
- **Miscellaneous groups: AIAA, AOPA.**

How can the industry be saved?

Due to the political nature of the problem, there is no simple solution to the problems facing the industry. However, some possible actions that could create an impulse in the right direction include lobbying Congress and the FAA, giving publicity to the problem through organizations such as the AIAA, and providing input to Congress through the CAAC.

In order to revitalize the industry, it is necessary for the private and miscellaneous groups to put pressure on the public groups:

- **GAMA can (and has) put pressure on Congress and the FAA to solve the product liability insurance problem and to improve certification procedures.**
- **AIAA can raise the issue in its meetings, articles, and competitions.**
- **Engineers and professionals can voice their concerns through the CAAC.**

How was M.E.G.A. designed?

The preliminary design presented in this report is the result of an iterative "cookbook" method, adopted from Wood's *Aerospace Vehicle Design, Vol. 1, Aircraft Design.* Additional concepts and estimates for "typical values" were obtained from other works, primarily Torenbeek's *Synthesis of Subsonic Airplane Design* and McCormick's *Aerodynamics, Aeronautics and Flight Mechanics.* Values for estimates were also taken from the specifications of existing general aviation aircraft designs, including the Cessna Skyhawk, the Beechcraft Bonanza F33A, and the Piper Archer II.

The M.E.G.A. design evolved from a combination of procedures presented by McCormick, Torenbeek, and Wood:

- **Power requirements, engine selection, weight and fuel estimates.**
- **Propeller selection.**
- **Lay-out sketch, weight and balance table.**
- **Airfoil selection.**
- **Static stability analysis.**

What were the initial specifications?

The initial specifications reflect the intentions of the M.E.G.A. design. Specific performance values were chosen to match current general aviation aircraft designs. The special features of the M.E.G.A. design appear primarily in the categories "equipment" and "arrangement". Here, the initial specifications were chosen so as to obtain a safe, yet simple and efficient design. Thus, specific items such as "3 lifting surfaces" and "split rudder" were chosen for system redundancy, whereas the "fixed landing gear" specification was chosen to keep the design simple and to reduce production costs.

Specification item:	Value:
A. Payload.	
1. Pilot and 3 passengers.	**360 kg (794 lb)**
2. Baggage (or 2 children on a folding seat).	**100 kg (220 lb)**
B. Performance.	
1. Range at cruising altitude (3000 m), no wind.	**1000 km (621 mi)**
2. High speed cruise at 3000 m, 75% power.	**90 ms^{-1} (120 mph)**
3. Landing speed.	**25 ms^{-1} (56 mph) ±5%**
C. Equipment.	
1. Electric starter.	
2. Two-way radio.	
3. Dual controls.	
4. Computer-assisted flight programming.	
D. Arrangement.	
1. 2 pairs of side-by-side seats and one folding seat for 2 children.	
2. 3 lifting surfaces (incl. canard) with uncoupled active control surfaces.	
3. Split rudder.	
4. No struts or external supporting structures.	
5. Fixed landing gear in tricycle configuration.	
E. Stability and control.	
1. Spin proof.	
2. Static margin at least $0.05\underline{c}$.	

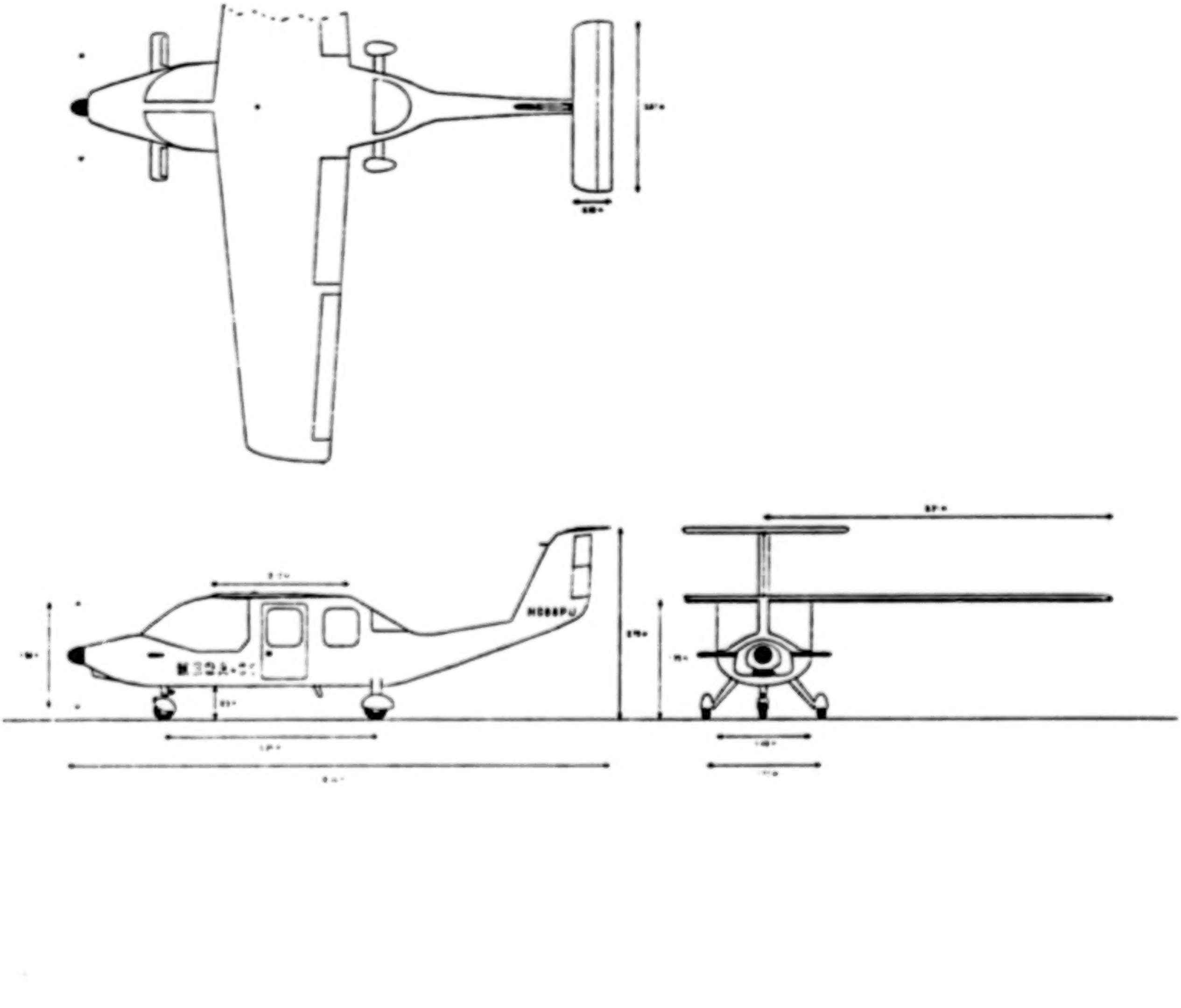
What were the design results?

Using the design procedure and initial specifications outlined above, a preliminary design was adopted. The engine selected is the new generation Porsche PFM 3200 air-cooled piston engine, with a take-off rating of 156 kW at 2,300 rpm. The airfoil section used is the NACA 65_2–215, which has a "drag bucket" near the design section lift coefficient. An untwisted wing with no dihedral was selected, with a 0.5 taper ratio. The wing and canard dimensions, as well as the resulting equivalent flat-plat area, are some of the results listed below. It should be noted that the design is stable in all configurations, with the static stability margin varying from 5% to 8%. Thus, the initial specifications concerning static stability are satisfied.

- **Porsche PFM 3200 air-cooled piston engine, rated 156 kW at 2,300 rpm.**
- **NACA 65_2–215 wing section.**
- $S_w = 16.6\ m^2$, $b_w = 10.4\ m$
  $\underline{c}_w = 10.4\ m$, $\lambda_w = 0.5$
- $S_c = 0.26\ m^2$, $b_c = 1.14\ m$
  $\underline{c}_c = 0.20\ m$, $\lambda_c = 1.0$
- $f = 0.334\ m^2$
- **Static stability margin 5–8%.**

Design lay-out.

This sketch shows the basic layout of the preliminary design. Note the large cockpit windows, the tri-plane configuration (with control surfaces on all lifting surfaces), the split rudder, and the T-tail configuration. For simplicity and low production costs, a fixed landing gear and an untwisted wing with no dihedral have been selected.



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Why a canard design?

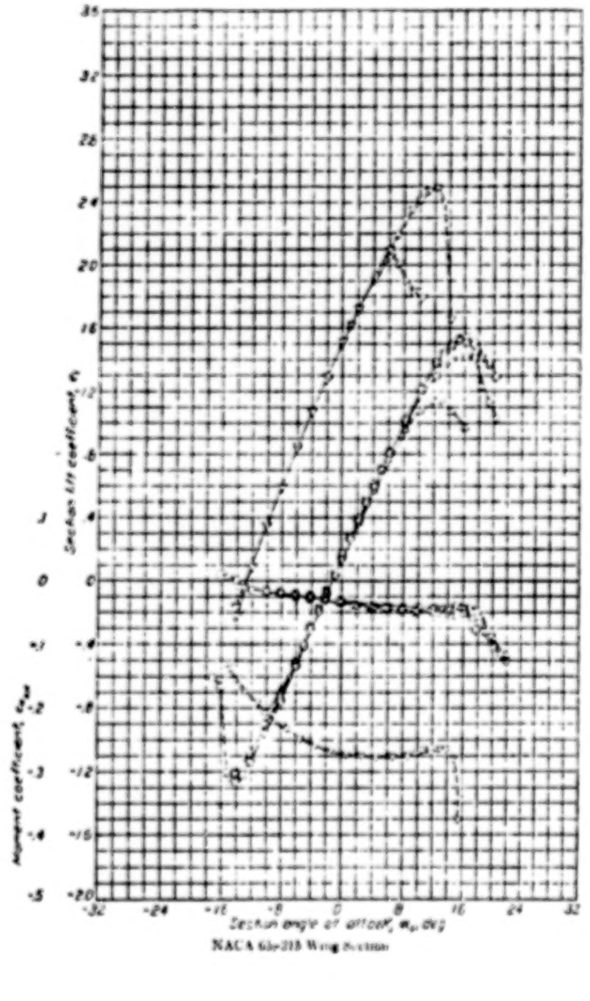
The use of a canard in the design of the M.E.G.A. aircraft deserves some attention, especially since general aviation canard designs have not gained extensive popularity. The purpose of the canard is threefold: The primary reason is that, due to the canard's position in the propeller slipstream, even a small canard will result in a high pitching moment at take-off. Thus, the negative lift normally produced by the tail to rotate the aircraft can be reduced, and overall take-off performance can be improved. Another advantage is that the area of the main wing can be reduced. Finally, the use of a tri-plane configuration allows the canard control surfaces to be used for back-up pitch control.

Since previous canard designs have in general not been very successful, special examination of this feature is needed:

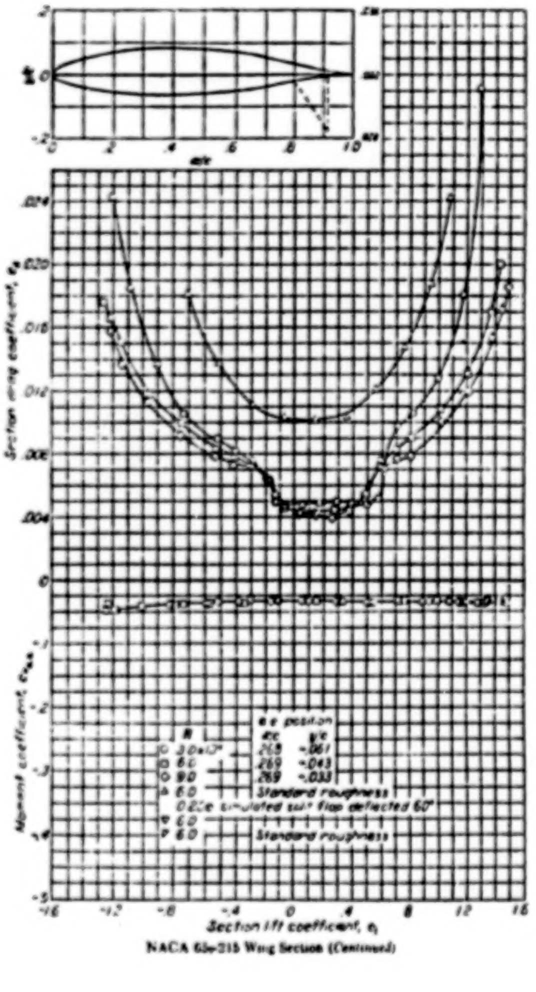
- **High pitching moment at take-off due to the canard's position in the propeller slipstream results in improved take-off performance.**
- **Wing area can be reduced.**
- **Canard control surfaces can be used for back-up pitch control.**

NACA 65_2–215 wing section characteristics.

The figures below show the wing section characteristics of the NACA 65_2–215 airfoil. The drag bucket around $C_l = 0.20$ is particularly important for the M.E.G.A. design, since it coincides with the design section lift coefficient in the cruise configuration.



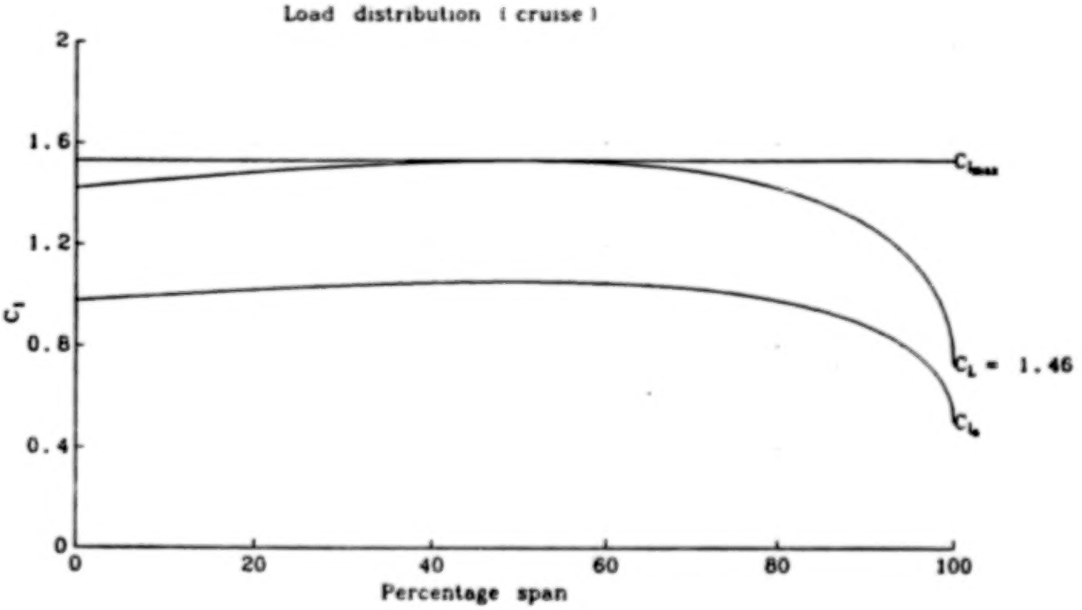
NACA 65_2-215 Wing Section

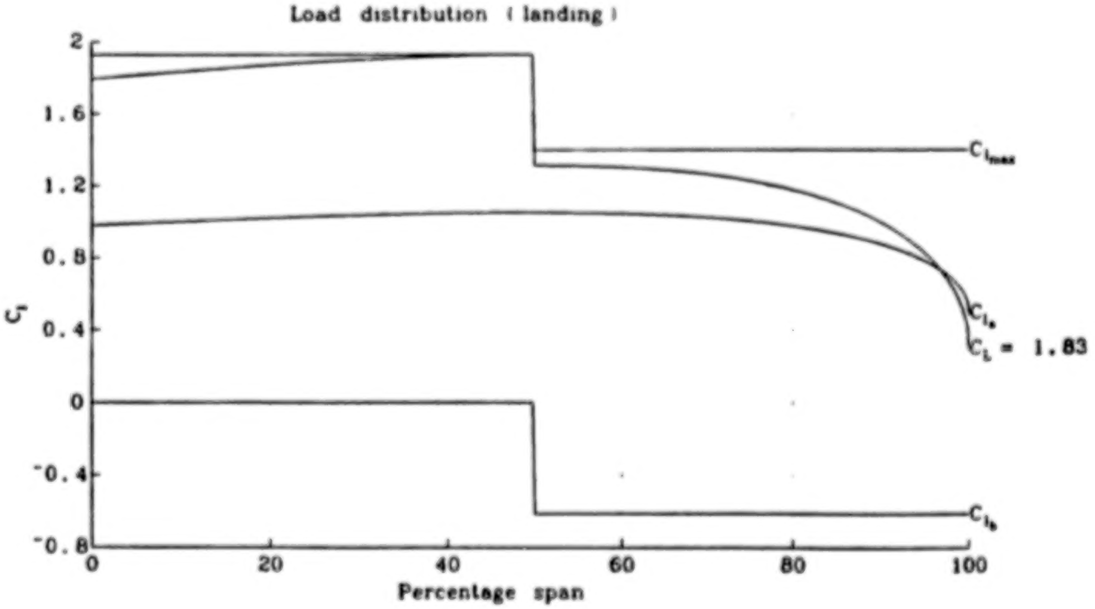


NACA 65_2-215 Wing Section (Continued)

Spanwise load distribution.

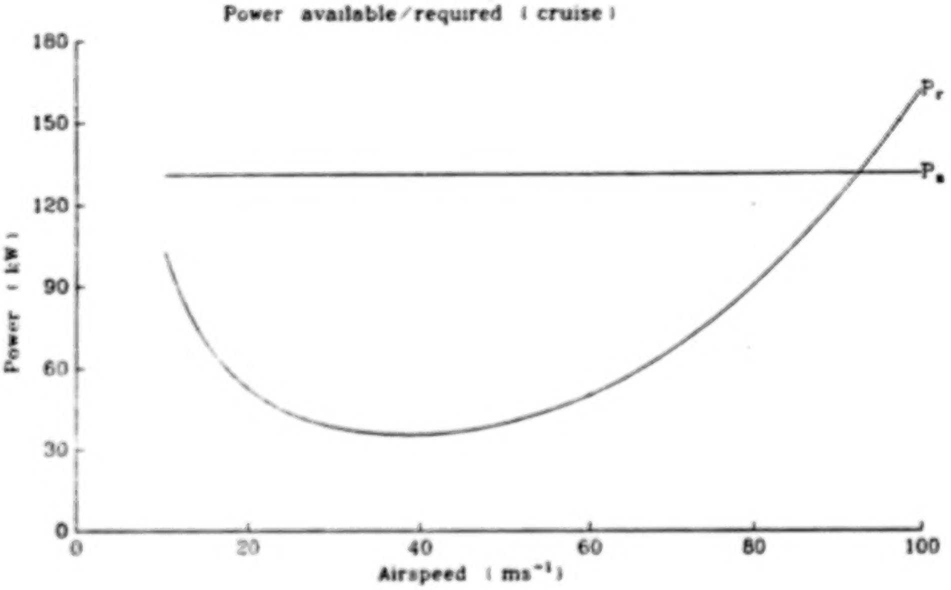
These figures show the spanwise load distribution in the cruise and landing configurations. The "basic" section lift coefficient (C_{l_b}) as well as the "additional" section lift coefficient (C_{l_a}) are also shown. The section lift coefficient is given by $C_l = C_{l_b}+C_{l_a}C_L$. The value of $C_{L_{max}}$ is obtained by finding the C_L in this equation that results in a C_l somewhere along the span which just equals $C_{l_{max}}$. In the landing configuration we obtain $C_{L_{max}} = 1.83$, which differs by only −3% from an initially assumed value of $C_{L_{max}} = 1.9$, obtained from Wood, *Aerospace Vehicle Design, Vol. I, Aircraft Design.*

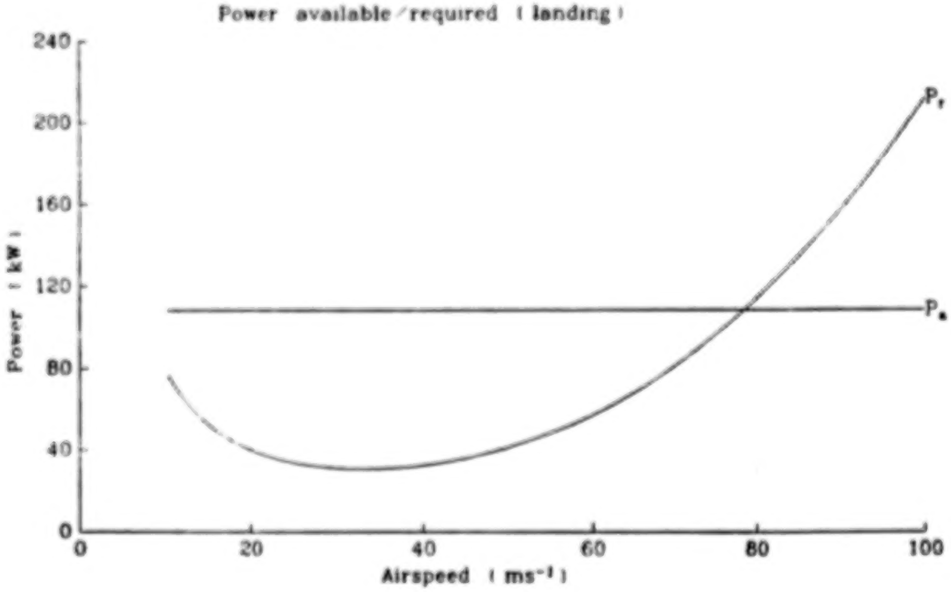




Power available/required.

These figures show estimates of the power available and the power required vs. true airspeed in the cruise and landing configurations. Note that since no specific engine data were available, except for the take-off rating, the power available was assumed to be a function only of propeller efficiency and percentage throttle used, and not a function of true airspeed.





What will be done in the future?

The current design is still very preliminary in nature and does not necessarily constitute an optimal one. More performance calculations and more design iterations are needed to optimize the design. Specifically, it is believed that the wing area can be reduced, and that the static stability margin can be increased. A dynamic stability analysis should also be performed. Furthermore, at this point in time, specific engine performance data for the Porsche PFM 3200 is not available. Future work will consist of the use of a multiple lifting surface analysis computer simulation, the construction of a scale model for wind-tunnel testing and liquid crystal flow visualization, and the construction of a quarter-scale remotely piloted vehicle to test the concepts of the M.E.G.A. aircraft.

- **More performance calculations, iterations, and optimization.**
- **Dynamic stability analysis.**
- **Inclusion of engine data.**
- **LinAir multiple lifting surface analysis (computer simulation).**
- **Scale model wind-tunnel testing and liquid crystal flow visualization.**
- **Quarter-scale RPV.**

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A SIMULATOR FOR FLIGHT THROUGH WIND SHEAR

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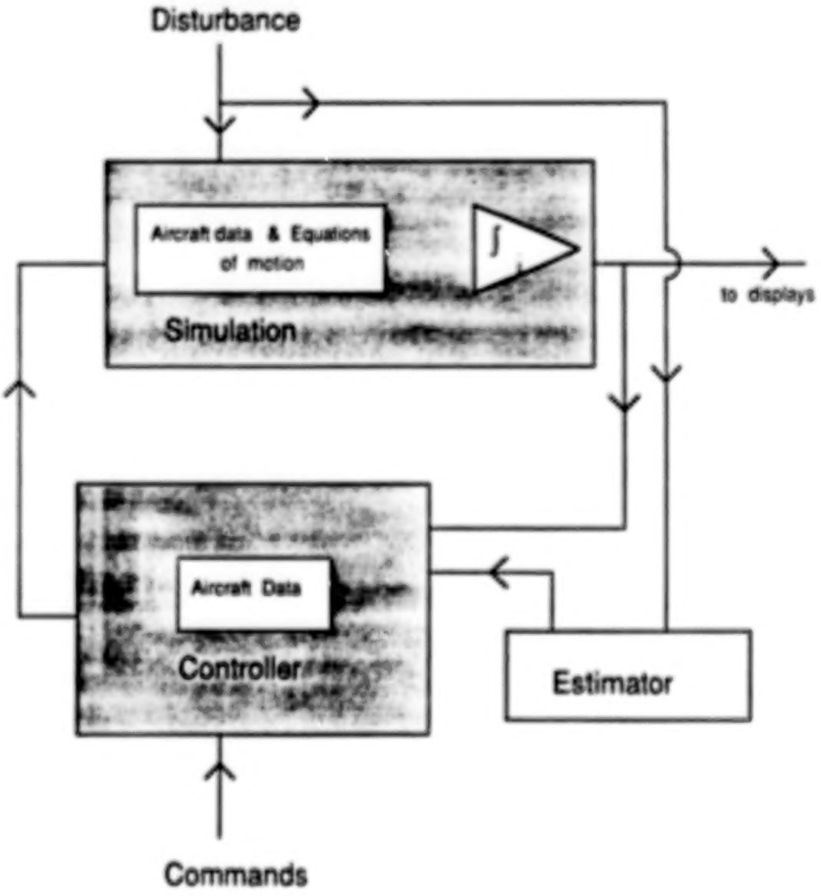
Introduction

The flight simulator now under construction at Princeton University is described. A functional and structural outline of the simulator is presented along with a report on the present status of the simulator. A particular problem faced is then elaborated upon.

- Overview
- TCP/IP
- Conclusions and future work

Overview of Simulator

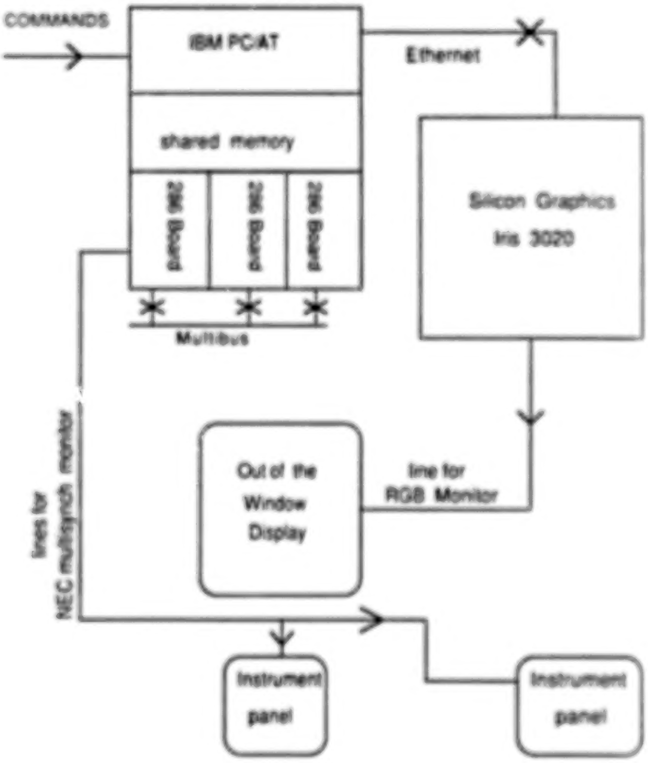
The simulator has a multiprocessor configuration. An IBM PC/AT computer is used for the overall coordination and control. The AT also performs the flight simulation calculations. The other components of the simulator include 3 Intel SBC 286 boards which perform the control law calculations. They are linked to the AT through a dual port RAM memory board. Two Matrox graphics boards produce the instrument panel displays. A Silicon Graphics IRIS 3020 workstation is used to generate the Out-of-the-Window display. The IRIS and the AT are connected over a high-speed Ethernet line. Currently, the various computers are in place and working.


Disturbance
Aircraft data & Equations of motion
∫
Simulation
to displays
Aircraft Data
Controller
Estimator
Commands

Overview of Simulator

(Functional)

From a functional point of view the simulator consists of 3 major blocks. The first is the simulation module which represents the mathematical model of the airplane. This is table driven, and it represents the nonlinear aerodynamic data of a jet transport aircraft. The second module is the controller. This contains its own set of aerodynamic data and is completely independent of the simulation. The third major module computes the graphics functions. The simulation module generates the states of the aircraft for a given set of controls. These are suitably modified to represent instrument and sensor errors and are then fed to the controller and display modules. The controller module generates the new control settings, and the graphics module the Out-of-the-Window display and instrument panel displays.

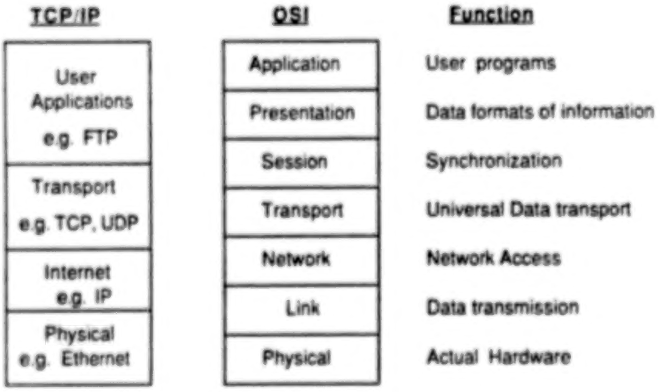

COMMANDS
IBM PC/AT
Ethernet
shared memory
286 Board
286 Board
286 Board
Multibus
Silicon Graphics
Iris 3020
lines for
NEC multisynch monitor
Out of the
Window
Display
line for
RGB Monitor
Instrument
panel
Instrument
panel

TCP / IP

One of the major bottlenecks in the simulator proved to be the link between the IRIS workstation and the AT computer. Initially a serial line was used but this proved to be too slow. Since there was an Ethernet in the lab, it was chosen. Off-the-shelf software drivers were not available in a format suitable for the simulator, so a package written for Packet radio was modified. The protocol used over the ethernet was the DARPA Internet Protocol (commonly known as TCP/IP).

The TCP/IP protocol suite is actually a family of protocols of various complexity. Typical examples are UDP (User Datagram Protocol), used for non-reliable data communication, and TCP (Transport Control Protocol), used for very reliable communication. The TCP/IP family forms a *layered* set of protocols. Another example of layered protocols is the OSI (Open Systems Interface). A typical layer structure is given in the figure, along with a short functional description.

- DARPA Internet Protocol Suite
- Covers a number of protocols
  - IP, UDP, ARP, TCP, FTP, TFTP, Telnet, SMTP . . .
- Layered Protocols
  - Independent , modular layers
  - OSI (Open Systems Interface), TCP/IP ...
  - Typical layer structure



TCP/IP	OSI	Function
User Applications e.g. FTP	Application	User programs
	Presentation	Data formats of information
	Session	Synchronization
Transport e.g. TCP, UDP	Transport	Universal Data transport
Internet e.g. IP	Network	Network Access
	Link	Data transmission
Physical e.g. Ethernet	Physical	Actual Hardware

TCP / IP
(Layers)

The TCP/IP protocol in particular can be looked upon as having 4 major layers. They are the Physical layer, the Internet layer, the Transport layer and the User application layer. The Physical layer is very hardware dependent. The Internet layer is a functional interface between the very hardware dependent physical layer and the very abstract Transport layer. The Transport layer provides the actual data transfer services to the User applications. In the case of the simulator, for speed and lack of any particular standard, a direct link to the Transport layer via sockets was used.

- Physical Layer
  - Ethernet, serial lines, computer bus, fiber optic link
  - Very hardware dependent, handles actual physical signals.
  - SLIP, ARP
- Internet Layer
  - Provides "minimum reliability" services,e.g. IP
  - Handles network errors ICMP
- Transport Layer
  - Completely device independent
  - Data handling services : TCP, UDP
  - Synchronization, timer and other such services.
- User Application Layer
  - Interface to "outside world"
  - Transparent access to other computers etc.

TCP / IP

(Other Issues)

There are many other aspects to the TCP/IP protocol. Most of these are not of concern in the flight simulator and so have not been addressed in any detail. Some of them are covered now in brief. For open systems there is a very important issue of unique addresses for each of the computers and for ease of use symbolic names. In the case of the flight simulator, since it is a closed system, this is not important. However to allow for external links addresses and names within the Internet, namespace alloted to the University has been obtained. There are issues, such as gateways fragmentation and windows, but these are of very little concern in the simulator and are mentioned here for completeness.

• Addresses	e.g.128.112.30.1
• Names	e.g. amit@isaac.princeton-lca.pucc.bitnet
• Gateways	IMP, routing, multiple protocol handling
• Fragmentation	
• Windowing	

The uses, advantages, and disadvantages of TCP/IP are summarized below in the self-explanatory figure.

TCP / IP

- Advantages
    - Reliable communications
    - Device independent user interface
    - Transparent
    - Standardized services
    - Easy to go to new hardware
- Disadvantages
    - Overheads
    - Complex software
- Use
    - Global Message passing
    - Modular and common communication
        - Easy to add more computers, remove computers
        - Easy and non-intrusive simulation monitoring
        - Supports multiprocessing in peer-to-peer mode

The figure below briefly summarizes the conclusions of material covered in this paper and gives recommendations for future work.

Conclusions and Future Work

- Ethernet communications are up and running.
- Need 'X' protocols for speed and modularity.
- Link pieces together.
- Need to carry out simulations

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